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COMMUNICATIONS LABORATORY



ADVANCEMENT OF HIGH RESOLUTION RADAR POLARIMETRY IN
TARGET VS. CLUTTER DETECTION, DISCRIMINATION,
CLASSIFICATION: A. Basic Theory and Modeling of
Polarimetric Clutter Phenomenology

W-M. Boerner, H.J. Eom, A.B. Kostinski, et al.

FINAL REPORT: 1988 July 15

Duration: 85-03-01 to 88-08-02

Contract No. ARO:DAAG 29-85-K-0065

Rept. No. #UIC-EECS/GI-ARO-EL/EM:88-07-15

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| Abstract The overall objective of our polarimetric research is to conduct a unified and cohesive investigation to answer the question: How can polarization properties of targets/background speckle be utilized either by themselves or in concert with other electromagnetic probing methods such as doppler, multispectral, pulse compression, etc., to best provide a basis for radar target classification, imaging, and identification? Scattering objects of interest include airborne/ground/marine targets of a large variety of sizes, shapes, and material decomposition and embedded in varied stationary/moving/fluctuating background scatter, which, we are confident, can most effectively be characterized via polarimetric radar/scatterometer methods including both coherent and partially coherent wave treatments. It is the specific objective of this task to approach and to investigate the polarimetric radar clutter problem using a unique approach of a strongly interdigitizing analytical, | | | | | |
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modeling, computer-numerical/graphical, and measurement interpretive nature. A basic theory for a model-independent clutter description which can be applied to any specific type of clutter without a priori knowledge of the clutter model, i.e., a model-independent clutter description, in theory, is introduced.

I.0 FOREWORD

From the outset of initiation (1985 March 01) of this research, we have concentrated on a strictly mathematico-physical revisitation of the basic polarimetric radar theory, dealing first with the purely coherent case and then with the more complicated partially polarized case. Thus, before developing a "basic theory and a modeling approach to polarimetric clutter phenomenology," we first analyzed the single stationary target case for both monostatic and bistatic measurement arrangements, which resulted in the correction of (i) basic standards on the definition of polarimetric scattering matrix measurements, and (ii) misconceptions in Kennaugh's, Graves', and Huynen's reports and expositions regarding the optimal (maximum and null) polarization state or (Kennaugh/Graves) polarization fork (Huynen) concepts. We were also able to introduce therewith the correct formulation of the polarimetric contrast optimization procedure and the polarimetric matched signal/image filter concept for the coherent case. After completing this task on setting matters straight for the coherent theory of radar polarimetry during the first and second fiscal periods (1985 March to 1987 Feb.), during the second and third fiscal periods (1986 March to 1988 Feb.), we reinvestigated the basic theory of radar polarimetry for the partially coherent case, resulting in our very important contribution on the optimal reception of partially polarized waves. On the basis of this basic contribution to radar polarimetry, we are now able to reinvestigate various polarimetric clutter modeling approaches, which we have accomplished for the cases of polarimetric rain backscatter and rough sea surface scatter, implementing dual polarization doppler radar measurements.

During the tenure of this contract, we were also fortunate to obtain polarimetric synthetic aperture radar (POL-SAR) measurement data obtained during the summer of 1985 by the CAL-TEC/JPL SAR imaging team with the NASA/JPL CV-990 L-band POL-SAR system, being the first POL-SAR system operational. With the utilization of this historical C-band POL-SAR imaging (scattering matrix on a pixel-by-pixel availability) data set of the San Francisco Bay area, we were then able to demonstrate the superb target enhancement versus background suppression capabilities of our polarimetric matched image filter approach.

In order to accomplish these set goals, at times we had to reprioritize and reorient our pre-set goals as described in the original and amended work statements of our proposal and contract. Therefore, in the following, we are presenting in Section I.1, the original and amended work statements; in Section I.2, the re-orientation and re-prioritization of the work statements; and in Sections I.3 and I.4 the overall and detailed important results are summarized. Sections I.5 and I.6 contain lists of technical reports and research interactions, and Section I.7 contains a list of publications. Section I.8 lists honors and awards of W-M. Boerner, Section I.9 summarizes thesis research in the UIC-EECS/CL, Section I.10 lists scientific personnel, and in Section I.11 the list of distribution is presented. In Section II important attachments are collected.

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ADVANCEMENT OF HIGH RESOLUTION RADAR POLARIMETRY IN TARGET VS. CLUTTER
DETECTION, DISCRIMINATION, CLASSIFICATION: A. Basic Theory and
Modeling of Polarimetric Clutter Phenomenology

(1985 March 01 to 1988 February 29/August 2)

FINAL REPORT

Wolfgang-M. Boerner, Hyo J. Eom, Alexander B. Kostinski, Amit P. Agrawal,
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1988 July 15

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PERSONNEL & FACILITIES

The research was carried out within the facilities of the UIC-EECS Communications Laboratory in SEL-4210/4211 using the UIC-EECS/CL research computer processing facility which possesses and operates two DEC VAX-11/750 host computers with advanced TEKTRONIX graphics, array processing, and image graphics/digitizing peripherals sponsored in part by the DOD-URIP (84/85) Equipment Grant No. DAAK 29-85-G-0002.

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PART I: TECHNICAL REPORT

I.0 FOREWORD

From the outset of initiation (1985 March 01) of this research, we have concentrated on a strictly mathematico-physical revisitation of the basic polarimetric radar theory, dealing first with the purely coherent case and then with the more complicated partially polarized case. Thus, before developing a "basic theory and a modeling approach to polarimetric clutter phenomenology," we first analyzed the single stationary target case for both monostatic and bistatic measurement arrangements, which resulted in the correction of (i) basic standards on the definition of polarimetric scattering matrix measurements, and (ii) misconceptions in Kennaugh's, Graves', and Huynen's reports and expositions regarding the optimal (maximum and null) polarization state or (Kennaugh/Graves) polarization fork (Huynen) concepts. We were also able to introduce therewith the correct formulation of the polarimetric contrast optimization procedure and the polarimetric matched signal/image filter concept for the coherent case. After completing this task on setting matters straight for the coherent theory of radar polarimetry during the first and second fiscal periods (1985 March to 1987 Feb.), during the second and third fiscal periods (1986 March to 1988 Feb.), we reinvestigated the basic theory of radar polarimetry for the partially coherent case, resulting in our very important contribution on the optimal reception of partially polarized waves. On the basis of this basic contribution to radar polarimetry, we are now able to reinvestigate various polarimetric clutter modeling approaches, which we have accomplished for the cases of polarimetric rain backscatter and rough sea surface scatter, implementing dual polarization doppler radar measurements.

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In order to accomplish these set goals, at times we had to reprioritize and reorient our pre-set goals as described in the original and amended work statements of our proposal and contract. Therefore, in the following, we are presenting in Section I.1, the original and amended work statements; in Section I.2, the re-orientation and re-prioritization of the work statements; and in Sections I.3 and I.4 the overall and detailed important results are summarized. Sections I.5 and I.6 contain lists of technical reports and research interactions, and Section I.7 contains a list of publications. Section I.8 lists honors and awards of W-M. Boerner, Section I.9 summarizes thesis research in the UIC-EECS/CL, Section I.10 lists scientific personnel, and in Section I.11 the list of distribution is presented. In Section II important attachments are collected.

I.1 ORIGINAL STATEMENT OF THE PROBLEM (Proposal No. P-22207-EL, 1985 Feb. 15, amended)

I.1.1 Title

Advancement of High Resolution Radar Polarimetry in Target Vs. Clutter Detection, Discrimination, Classification, Imaging & Identification: Basic Radar Clutter Description, Modeling, Simulation, Metrology: Target in Clutter Discrimination

I.1.1.2 Summary

In the development of special purpose tactical radars employing advanced high

resolution polarimetric target detection modes, the problem of accurately determining the properties of "clutter" is still not adequately resolved. In this research project an interdigitizing theoretical, analytical, modeling, metrological, computer-numerical, and model verification approach is used to analyze indepth polarimetric broadband clutter description as it pertains to target detection in clutter at meter to sub-millimeter wavelengths. Specifically, theoretical clutter models based on the optimal polarization clutter null theory (mean null coordinates and spread of cluster) and the multiple vector scattering center clutter descriptive approaches are analyzed and the even (manmade metallic target) versus odd (natural scatter ensembles) multiple bounce scatter interpretation, Huynen's N-target decomposition theory and the polarization matched clutter suppression filter technique are being scrutinized. The main objective is to determine the optimum polarimetric transceiver design for discriminating targets in clutter.

I.1.1.3 Objective

The objective of this research is to approach and investigate the polarimetric radar clutter problem using a unique approach of a strongly interdigitizing analytical, modeling, computer numerical/graphical and measurement interpretive nature. The analytical, modeling, and computer verificational research tasks will be carried out within the facilities of the Communications Laboratory (CL), Electrical Engineering & Computer Science Department (EECS), University of Illinois at Chicago (UIC), utilizing the DEC-VAX 11/750 plus 785 Research Computer Processing facilities in SEL-4210/F and 4211/G&M with peripheral vector/color graphics and image processing/printing facilities.

We will require extensive polarimetric radar measurement data on various specific kinds of natural and/or manmade clutter which includes terrain/tree/vegetation/forest/crop/agricultural scattering sites with or without snow cover, meteorological cloud/fog/rain/hail/electric storm scatterer ensembles, and sea scatter within the marine ocean boundary layer. Because, at the present time, we do not have our own Advanced High Resolution Polarimetric Radar System available, in the interim period, polarimetric measurement data collected at other DOD/NATO/Industrial R/D/M facilities will be used.

These basic studies will be of paramount importance to the development of advanced polarimetric seeker radar systems. Consequently, we are going to work closely with the US Army Research & Development Centers & Commands and the national radar industry who are involved in the development of polarimetric radar seeker systems, and the R&D centers of the US Navy and Air Force.

I.1.1.4 Research Problem Identification

The specific research problems to be investigated represent an integral part of the overall research activities carried out within the Communications Laboratory, UIC-EECS, on polarization utilization in target/clutter handling and may be described as

"Basic Radar Clutter Description, Modeling, and Simulation for Non-Cooperative Radar Target Detection/Discrimination in Clutter."

Based on the literature review of Section I, and the background theory presented in Chapter II, (ARO Proposal #22207-EL) the following specific research problems have been identified.

Basic Theory and Modeling of Polarimetric Clutter Phenomenology

(A model-free, self-consistent approach for polarimetric clutter description on the polarization sphere applicable to various types of clutter).

It is the objective to introduce a basic theory for clutter description which can be applied to any specific type of clutter without a priori knowledge of the clutter model, i.e., a model-free clutter descriptive theory.

As a first step, the model-free clutter theory will be derived using a coherency matrix [J], or equivalently, a Stokes vector [g] measurement approach. Using the concept of ensemble (phase) averaging over repeated sets of measurements within time frames below the scattering center reshuffling time, it will be shown how the 4 x 4 ensemble averaged Mueller matrix [M] can be related to the mean Sinclair matrix [S], and the locations of the mean polarizations and its spherical spread about the means on the polarization sphere to be derived. The relationship between the coherency matrix in our "model-free" clutter descriptive theory and the "model-free" N-target decomposition theory of Huynen will be established showing its congruence. For the verification of the two congruent model-free clutter descriptive theories, basic clutter descriptive statistical models have to be generated for various kinds of clutters including terrain/sea/meteorological/vegetation, such that the mean clutter null polarization and their spherical variance about the mean can be extracted and related to specific clutter descriptive parameters. For this purpose, two principally suitable approaches exist: (i) that of extending the vector scattering center dumbbell model developed in

H. Mieras, R.M. Barnes, G.M. Vachula, J.N. Buckham, C.L. Bennett and W-M. Boerner, "Polarization Null Characteristics of Simple Targets," Sperry Research Center, SRC-CR-82-83, Contract NO. F-30602-82-C-0254, 1983,

to that of compactly packed scattering centers (i.e., scattering center ensembles representing a specific type of clutter); and (ii) employing the multiple reflection bounce principle introduced in Part I, Section 3 (See ARO Proposal #22207-EL). These two methods will be combined to generate specific clutter models using combinations of spheres, di/trihedral reflections, contips, linear dipoles, left/right sensed helices, etc., as individual scattering center models with deterministic as well as statistical distribution models. The major objective is to prove and verify the clustering properties of the clutter null polarizations on the polarization sphere, and to show how the location of the mean clutter nulls and its spherical spread about the mean can be utilized to straight-forwardly extract basic clutter descriptive parameters.

I.1.2 Work Statement of Specific Tasks

In the following, detailed work statements for each of the three rather closely related research tasks are presented, with identification of research supervisory staff, graduate research assistant (Ph.D./M.Sc. candidates) staff, source of measurement data, and computer-numerical/graphical facility requirements.

Note, that the research staff involved in this set of research tasks belongs to the Remote Sensing and M-to-Sub-MM Wave Propagation Group of the Electromagnetic Imaging Division within the Communications Laboratory/UIC.

Basic Theory and Modeling of Polarimetric Clutter Phenomenology

(A "model-free" self-consistent approach for polarimetric clutter description on the polarization sphere applicable to various types of terrain, meteorological and sea clutter).

| | |
|--------------------------------|---|
| Principal Investigator: | Prof. Wolfgang-M. Boerner |
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| Research Scientist: | Dr. Alexander B. Kostinski |
| Grad. Res. Assistants: | Mr. Amit P. Agrawal (Ph.D.) Mr. Jonas Okeke, M.Sc. |
| Visiting Research Consultants: | Dr. J. Richard Huynen (FYI) Dr. Shane R. Cloude (FYII) |

I.1.2.1 Specific Task Description

a) Extraction of Mean Clutter Null Polarization and Their Spherical Spread from Coherency Matrix Measurements (Agrawal/Nespor/Okeke)

In the M.Sc. thesis of J.D. Nespor it was shown how the Stokes vector of the receiver antenna can be related to that of the transmit antenna not only via the Mueller matrix, but with the use of the coherency matrix and adopting the concept of the "pulse and phase ensemble averaging" of the elements of the Sinclair radar scattering matrix $[S]$. It was then shown how the mean clutter polarization nulls and their spherical spread (variance) about the mean can be obtained from a coherency matrix measurement approach and that the mean clutter null coordinates on the polarization sphere and its spread can be related either to the coherency factor or the depolarization factor plus descriptive parameters of the specific clutter under investigation. We have proven that the spherical spread about the two cross-pol. and the two co-pol. nulls are the same for the clutter.

In a next step, we have shown (Nespor, Agrawal, Boerner, 1984) that the spherical spread about the two mean co-pol. null and the two mean cross-pol. null locations on the polarization sphere is the same for all which provides the link to Huynen's N-target decomposition theory (Huynen, 1981, 1982 a,b, 1983, 1984).

b) Relation between Huynen's N-Target Decomposition Theory and the Mean Clutter Null Description for the Monostatic Reciprocal Scattering Case

In Part II, Section 4 (ARO Proposal #22207-EL), it was shown that for the monostatic reciprocal coherent scattering case, the relative scattering matrix $[S]$ contains five independent real quantities whereas for the quasi-coherent case, $[S]$ cannot be used formally, but $[M]$ which possesses nine independent real quantities can be used. For the coherent case, it can be shown that the five independent parameters of $[S]$ represent the radius of the associated polarization sphere being equal to $\text{span } [S]$, and the spherical coordinate pairs $(\theta_{1,2}, \phi_{1,2})$ of either both co-pol null or one co-pol and one cross-pol null locations on the unit polarization sphere (Kennaugh, 1952; Huynen, 1970). For the incoherent case, the mean co-pol. null and cross-pol. nulls can then be expressed similarly in terms of five independent quantities, leaving four undetermined quantities which can be identified to be the four isotropic clutter spread spheres each centered in the mean coordinates of the four optimal polarization nulls. Thus, all the nine independent quantities of $[M]$ for the monostatic, reciprocal scattering case are uniquely determined in terms of "model-free" mean clutter polarization null descriptions as was first derived using a coherency matrix approach (Nespor, 1983) and further extended (Nespor, Agrawal, and Boerner, 1984).

Huynen (1970), on the other hand, attempted a logical approach of decomposing the incoherent matrix $[M]$ into "the mean target matrix $[M_m]$ and the target residue" as is shown in Part II, Section 1 (ARO Proposal #22207-EL), for some specific clutter cases represented chaff (Ioannides and Hammers). However, a deep physical insight to the target residue or noise has not been given anywhere to date.

We note here, however, that the mean target matrix $[M_m]$ corresponds to a coherent-like matrix $[S_m]$ which is defined by five independent quantities, whereas target residue contains four independent quantities. We now need to show the congruence of our mean clutter polarization null description with their spherical spread and Huynen's N-target decomposition theory.

c) Application of the Mean Clutter Polarization Null Description to Specific Clutter Cases

In a first successful attempt, Nespor (1983) applied the "model-free clutter description" to the interpretation of hydrometeor scatter showing how the mean cross-pol. null location can be directly related to the canting angle of raindrops and how the mean co-pol. null locations relate to the drop shape which will be analyzed in great detail (Agrawal, Nespor, Boerner, 1984). We note here that our preliminary results have also been independently obtained by McCormick et al. (1984 a/b). Currently, our analytical results are being tested using relative phase scattering matrix results provided by Mr. A. Hendry/Dr. McCormick, NRC-Ottawa.

Similarly, we are now extending a similar analysis to the interpretation of complete relative scattering matrix measurement data of various sea clutter cases provided by both NADC-Warminster, PA and BAC-KCS-Kent, WA (Nespor, Agrawal). Our preliminary results show again that our "model-free" approach provided a useful tool for extracting useful parameters.

It is the prime objective to apply our model-free polarimetric clutter descriptive approach to the analysis of clutter generated by rough terrain with and without vegetation, forestial, hydrometeorological, dust, fog, etc., cover in which cases it is useful to separate surface from volumetric distributed scattering center, where surface scatter usually is less dependent on polarization than distributed volumetric scatter (Fung and Eom, 1981-1984).

1.1.2.2 Measurement Data Acquisition

During the past years, we have established close contacts with various R&D Centers involved in the generation of polarimetric clutter measurements in the various frequency bands of the m-to-sub-mm wavelength region. This interaction is currently strengthening, and in the following the major suppliers of clutter measurement data are listed.

Note, due to the proprietary nature of measurement data exchange agreements only limited information is being provided here, and any other detailed information will be provided only to the ARO-Electronics Division upon specific request.

Hydrometeor Clutter (S,L,C,X-bands)

| | | |
|-------------------|-----------------------------------|-----------------------|
| NATO/SHAPE-TC | C,X-band | Dr. Andre J. Poelman |
| Scheveningen | [SMR(H,V)] | (already available) |
| The Hague, NC | rain/cloud/electric storm scatter | |
| NRC-EMD-RS | L,S,C-band | Mr. Archibald Hendry |
| Montreal RD Labs | [LMR(H,V)] | (already available) |
| Ottawa, Ont. | rain/cloud/electric storm scatter | |
| DFVLR-OPH | L-band | Dr. Arno Schroth |
| Oberpfaffenhofen, | [S(A,B)] | (available as soon as |
| FRG | general meteorological clutter | DFVLR-MET-Radar is in |
| | | operation:1986/87) |
| ISWS-MRD | X,S-band | Dr. Eugene A. Mueller |
| Champaign, IL | polarimetric radar | (already available) |
| | (incomplete polarimetric) | |

Sea Surface/Hydrometeor Clutter (S,L,C,X,K-bands)

| | | |
|-----------------------|--------------|----------------------|
| NADC-Molokai | L,S,C,K-band | Dr. Otto Kessler |
| Warminster, PA | [S(H,V)] | |
| Boeing Aerospace | 17,36,94 GHz | Mr. Kenneth Williams |
| Corporation | [S(H,V)] | Mr. George Swetnam |
| Kent Space Center, WA | | |

Rough Surface/Terrain Scatter

| | | |
|----------------------|------------|-------------------|
| MICOM-DRSME-REG | X,K-bands | Mr. Lloyd W. Root |
| Redstone Arsenal, AL | [LMR(H,V)] | |

I.2 RE-DEFINITION, RE-ORIENTATION, AND RE-PRIORITIZATION OF THE STATEMENT OF WORK

The Research Task A. "Basic Theory and Modeling of Polarimetric Clutter Phenomenology," must be considered a subtask of an initiation project which was carried out under ERADCOM/DELCS/HDL/DELNV No. DAAK 21-84-C-0101 (Solicitation No. DAAK 84-R-9150) (1983 July to 1985 Oct.) on:

"Stationary Target Detection and Classification Algorithm Development
Applied to Armored Vehicle Detection in Ground & Tropospheric Clutter,"

with the objective:

"to develop and evaluate high range resolution, polarization diverse algorithms, and to detect and classify stationary and moving targets in clutter."

Although our final proposal of July 1984, contained very specific and detailed workstatements, the Statement of Work for Contract No. DAAK21-84-C-0191 was brief and succinct, and in one paragraph, described in what ought to be the objective of the entire U.S. Army/DARPA/Air-Force MMW air-to-ground seeker radar effort, quote:

"The contractor shall develop the strategy by which a high range resolution, polarization diverse meter-to-millimeter wave radar will be used to reliably detect and classify stationary vehicular targets in clutter. The contractor shall develop mathematical descriptors based on polarization returns of multiple reflection bounce objects in isolation and in clutter. The Contractor shall develop mathematical models of unarmored and armored vehicles based on the combination of simple geometrical shapes and more complex individual scatterers for each vehicle. Theoretical clutter models and target models shall be analyzed for predicting the distribution of polarization returns so as to generate target detection and classification algorithms. The Contractor shall identify the procedure by which more varied military tactical targets will be modeled and provide predictions of significant individual scatterers that might be used in classification algorithms. The Contractor shall develop first level algorithms for discrimination of targets from clutter (i.e., detection of targets in clutter) and deliver these models and algorithms to the government for test against real data."

Anyone familiar with this complex subject matter will comprehend that the workstatement presented to us will require the combined R&D efforts not only of the radar research laboratories of the US Army, but the dedicated collaborative efforts of all interdisciplinary/institutional R&D centers of the National Radar Industry, Academic Basic Research Institutes and Governmental Research Laboratories.

Therefore, to be productive, the workstatement given to us had to be comprehended in its entirety, identifying the many related but distinct research problems, setting priorities and suggesting a viable path of approach which will provide useful partial results. For the purpose of illustrating these complexities, the Initiation Report, "Development of Polarimetric Target Characteristic Classification Algorithms Applied to Armored Vehicles," for ERADCOM-DELCS/Ft. Monmouth was put together rather hurriedly. In spite of the

severe criticism we received, which is constructive and must be accepted, we suggest a careful study of the concluding sections outlining the overall scenario of solved and unsolved problems. Here, we also refer to the recent report (Dec. 1983)

W-M. Boerner, "Advancement of High Resolution Radar Polarimetry in Target vs. Clutter Detection, Discrimination, Classification, Imaging, and Identification - Part C: Recommendations for New Research Efforts in Radar Polarimetry - Benefits for National Research Effort,"
(updated version contained in Part II)

which certainly had considerable influence in shaping the DARPA-TTO JAWS (Joint All Weather Seeker) and ADTS (Advanced Detection Technology Seeker) programs and also was used by us to readdress the polarimetric radar research problem. Here, we are reproducing the diagrammatic chart identifying the specific disciplines which still require in depth strong attention on the 6.1/6.2 level funding before 6.3 level development projects can evolve with reliable results.

Here, we refer to the final report produced under the ERADCOM/HDL Contract No. DAAK 21-84-C-0101

W-M. Boerner, A.B. Kostinski et al., Stationary Target Detection/Classification Algorithm Development Applied to Armored Vehicle Detection in Ground/Tropospheric Clutter, Final Report, Contract No. DAAK 21-84-C-0101, 1985 Oct. 14, Rept. No.: UIC-EECS/CL: ARO/HDL 85-10-14,

in which details on our assessment of the shortcomings of the Huynen N-target decomposition theory are provided. For a more detailed analysis, we refer to the Final Report prepared under a NADC Contract, entitled

W-M. Boerner et al., Graphical Depiction of Targets Using Polarized Radar Data, Final Report, NADC Contract No. N-62269-85-C-0383 (Soc. No.: N-62269-35), 1987 June 15, UIC-EECS/CL/NADC 87.06.15, NADC 87163-50,

where in Chapter III, a critical review of Huynen's parameters is given.

| National Forum of Experts | | | |
|--|-----------------------------------|--|--|
| Appointed National Coordinator: | | Government: Industry: Academia: | Workshops Panel Discussions |
| BASIC TECHNOLOGY | METROLOGY | VECTOR SIGNAL/IMAGE PROCESSING | HARDWARE COMPONENT, DEVELOPMENT & SYSTEMS DESIGN |
| Basic Polarimetry | Basic Experimentation | Pulse Compression in Radar Polarimetry | Electronic Hardware |
| Target Phenomenology | Polarimetric Data Collection | Polarimetric Doppler | Polarization Antennas |
| Clutter Analysis | Radar Metrology | Vector Signal Processing | Polarization Transceiver |
| Vector Inverse Scattering | Ground Truth Metrology | Vector Image Processing | Pulse Doppler/FM-CW Chirp |
| Target-Clutter Interaction | Measurement Data Basic Processing | Algorithm Development: Classification/Identification | Algorithm Robotics |
| Vector Imaging | Imaging Systems (SAR/RAR/ISAR) | | Polarization Signature Display |
| DEVELOPMENT OF MODULAR TEST-BED DESIGN OF BROADBAND HIGH RESOLUTION POLARIMETRIC COMPRESSION PULSE DOPPLER RADAR SYSTEM: TESTING, COST-TRADE-OFF/TECHNOLOGY ANALYSIS | | | |
| TECHNOLOGY TRANSFER TO INDUSTRY | | | |

Figure 1: Advancement of Polarimetric Radar Technology (Prepared December 1983)

I.2.1 Re-Definition and Re-Derivation

We require another completely new look and deeper analysis of the entire polarimetric radar research problem, because the existing theories of Kennaugh and Huynen are incomplete and/or incorrect and require re-assessment and extension. Certainly, there now exists ample evidence that "polarization utilization plays an important role in M-to-MMW radar target detection/classification/imaging/identification"; the question, however, is how to fully use such extra information.

Not discouraged by the "immense globality" of this complicated problem, we set to work with enthusiasm, and made good use of our extensive background knowledge of the field which, more or less, includes comprehension of the entire literature (open as well as classified) on "radar polarimetry," separating this complex problem according to the diagrammatic chart of Fig. 1, and pursued in order of priority: **theory, metrology, and signal processing** aspects of the UIC-EECS/CL and the **polarimetric hardware and polarimetric transceiver systems design** within Polarimetrics, Inc.

Therefore, during FYI/FYII, we concentrated on the fundamentals of radar polarimetry, first treating the coherent case and slowly attacking the partially coherent case as reported in summarizing detail in the semi-annual reports, with back-up sub-task reports. Only after the basic theory has been set straight, can we move ahead and address the more complicated target in clutter detection and target classification algorithm development problems.

Consequently, during FYI to FYII, we abandoned all attempts of developing any target detecting/classification algorithms, per say, but rather concentrated on reassessing, correcting and updating the underlying polarimetric theory using all available research resources for this most essential and important first step. We are confident in considering ourselves to be one of the top research teams in the field of advancing high resolution radar polarimetry and we are sincerely convinced that with the available research staff we have served the interests of the U.S. Army best.

I.2.2 Re-Prioritization/Timing of Specific Work Statement Tasks

We are aware that there already exist some rather powerful target detection and classification algorithms using high range resolution combined with polarization diverse MMW radar measurement data. Furthermore, we are also aware that these more recently derived target detection/classification algorithms by no means can be considered ultimate and in fact are still not sufficient to be applied in real-time battlefield applications (see Section I.4). In order to find and establish the most superior detection/classification algorithms which we are very confident are being provided by NATURE, we have initiated a "major offense" on the foundations of radar polarimetry and assessed its application to the problem under consideration with laborious and painstaking efforts. Therefore, we are convinced that our step-by-step approach adopted during the initiation of this contract task is the only possible proper path to obtain superior radar target detection/classification algorithms using complete high resolution range/cross-range/polarimetric broadband and doppler information.

A. Basic Technology

The following prioritization/timing of the overall approach to overall problem of algorithm development for stationary target detection & classification in clutter within the m-to-sub-mm-wavelength region: During FYI major and all emphasis need to be placed on reassessing the basic polarimetric radar theory, from an electromagnetic diffraction/scattering point of approach. Here, we must stress that no useful algorithms can be developed without first having

established the correct theory based on solutions of the following problems:

Polarimetric Radar Theory (FYI)

Reassessment of definitions of polarization state (vector versus spinor interpretation); scattering matrix decomposition (target characteristic operator: optimal polarization states); uniqueness proof for use of "p-formulated unitary transformation matrix" in radar polarimetry; coherency matrix/Mueller matrix formulations in radar polarimetry.

Radar Target Phenomenology (FYI+II)

Reassessment of radar target phenomenology introduced by Kennaugh, Huynen, Poelman et.al.; redefinition of target characteristic operator (the polarization fork); introduction of the "Three-Stage Scattering Matrix Optimization Procedure"; critical assessment of Huynen's Mueller matrix decomposition theory.

Clutter Analysis (FYII+III)

Development of model-free clutter descriptive theory based on the polarization fork approach; verification and interpretation of the clutter polarization null clustering phenomenon on the polarization sphere; rain/sea scatter and vegetative/terrain scatter modeling.

Vector Inverse Scattering (FYI to III)

Establishment of relationship between target geometry/material properties and the scattering matrix elements: Polarimetric vector extension of Kennaugh's target characteristic operator theory.

Target-Clutter Interaction (FYIII beyond)

Use of the "Three-Stage Scattering Matrix Optimization Procedure" for target versus clutter discrimination; development of simplified target/clutter classification principles.

Vector Imaging (FYI to III, beyond)

Combination of high range/cross-range information with complete range-bin/pixel scattering matrix data for the development of "polarimetric matched filter techniques" for target versus clutter separation in high resolution polarimetric SAR/RAR/ISAR.

B. Metrology (FYI: Initiation; FYII and beyond)

Hand-in-hand with developing the underlying polarimetric radar target/clutter theory, we need to take a fresh, unbiased look at polarimetric metrology for the purpose of obtaining the proper measurement inputs for target detection/classification algorithm development. During the past six years and particularly during FYI, considerable efforts were also expended in this area.

Basic Polarimetric Experimentation (FYI; continued)

(Due to the highly proprietary/classified nature of these research aspects the main efforts were carried out through Polarimetrics, Inc. rather than UIC Project activities.) Reassessment of existing polarization radar design approaches and development of new polarimetric measurement principles.

Polarimetric Data Collection (in progress)

Establishment of our own UIC-EECS/CL library on complete polarimetric scattering matrix measurement data for targets which include missile-type military ground based, naval, air targets; and for various kinds of clutter including meteorological (rain/fog/storm), sea and coastal, vegetative terrain and battlefield types.

Radar Metrology (in progress)

Provide advise in conducting better, more reliable and reproducible polarimetric radar target/clutter measurements for monostatic, forward and bistatic plus multistatic scattering.

Ground Truth Metrology (FYII and beyond)

It is impossible to develop reliable and reproducible results in the real-time application of target classification/identification algorithms without also paying the rather exorbitant price of establishing a solid ground truth metrology. The entire M-to-MTW Seeker radar effort is suffering the most detrimental lag in this important department. Therefore, in simultaneity with the ongoing inhouse UIC-EECS/CL research, great efforts need be expended to assist industry and governmental laboratories to improve most rapidly their methods, techniques and resources in a more accurate and completed ground truth assessment and metrology.

Polarimetric SAR/RAR/ISAR Imaging Sysem (FYII and beyond)

Development of pixel-by-pixel, range-bin-by-range-bin polarimetric scattering matrix measurement and recording techniques of polarimetric matched filter post-processing.

Polarimetric Calibration Target Selection (FYI, continued)

Currently, as in the past, in radar polarimetry we are still at a loss in defining the most suitable set of calibration targets in isolation and distributed settings. It is thus one of the foremost objectives to advance polarimetric calibration target metrology.

Polarimetric Measurement Data Pre-Processing (FYII, beyond)

In conjunction with the above sub-tasks, the measurement data pre-processing must be developed from an entirely new point of view incorporating polarimetric calibration standards with exact amplitude and phase reference standards; extraction of unwanted range/azimuth dependence, and with sensitive ground truth correlation.

C. Vector Signal/Image Processing: Algorithm Development for Target Detection/-Classification and Identification (FYII and beyond)

Polarimetric radar algorithm development for stationary and/or moving targets requires first the solution for sub-tasks of Problem Areas A and B as well as specific sub-tasks of vector signal/vector image processing which include the following:

Assessment of Stationary Target Detection Radar Modes of Operation

Development of multi-sensor, multi-function polarimetric radar/scatterometer techniques using both monostatic, forward and general bistatic and combined multistatic operations.

Pulse Compression for High Range/Crossrange Resolution in Polarimetric Target Signature Mapping of Stationary and/or Moving Targets

Various existing and recently proposed methods of polarimetric pulse compression radar techniques including IPPAR need to be compared, assessed, simulated, and experimentally verified.

Polarimetric Doppler Development for the Early Detection of Hydrometeoric Mass Vortex Motion

The recent incidence of aircraft crashes due to hydrometeoric mass downbursts, cyclonic motions and shear-stress turbulence have given new impetus to the rapid advancement of polarimetric doppler techniques which should be especially perti-

nent to the detection of stationary targets embedded in ground/background clutter in a hostile stormy battlefield environment.

Polarimetric Vector Signal Processing

Based on the research and signal processing development of Vannicola et.al. and Poelman et.al., adaptive five (nine) channel vector signal processing techniques need to be developed hand-in-hand and properly understood for optimum algorithm development.

Polarimetric Vector Image (Signal) Processing

In the entirely new and highly promising field of polarimetric scattering matrix SAR imagery as introduced in

NASA/JPL Aircraft SAR Workshop Proceedings
February 4-5, 1985, at the Jet Propulsion Laboratory
Pasadena, California
Edited by N. Donovan, D. Evans and D. Held
Report No.: JPL Publication 85-39 (June 15, 1985)

we now require the immediate development and advancement of polarimetric matched filtering techniques which may assist us, most likely with the highest superiority above any other available technique, when applied to the cm-to-sub-cm-wavelength region in the detection, classification, and imaging of stationary natural and/or man-made targets in similar natural and/or man-made background clutter.

Algorithm Development Using High Resolution Polarimetric Radar Technology

Classical methods of image and picture processing have been advanced very strongly during the past two decades; however, very little was done to apply these methods systematically to algorithm development for pattern recognition in polarimetric vector signal and vector/tensor image processing. We are now proceeding with the imaging/identification development of:

- (i) polarimetric matched filter techniques for double cross-range (SAR) image processing,
- (ii) the Three-Stage-Polarimetric Target Signature Optimization procedure, and
- (iii) the polarimetric multi-function/multi-spectral/multi-static target detection/classification algorithms.

I.3 PROGRESS IN OUR PAST/CURRENT POLARIMETRIC RADAR/SAR RESEARCH AT UIC-EECS/CL

I.3.1 Overall Progress

During the past ten (10) years, basic research on the fundamentals of coherent and partially coherent radar polarimetry were carried out within the UIC-EECS/CL with applications to target detection in clutter, target and background clutter classification, target imaging, and identification. As a result of these investigations the underlying fundamental theory of polarization radar technology was revised and corrected and generalized, and the related polarimetric radar target phenomenology, originally introduced by Dr. Edward M. Kennaugh was reformulated in a physically more transparent three-stage target versus clutter optimization procedure. Also, we have clarified existing misconceptions about the valid use of the restricted p -formulated unitary transformation matrix presentation of the optimal polarization Null/Max theory of Kennaugh and Huynen in the monostatic cases. Simultaneously, electromagnetic vector inverse scattering theories which utilize complete relative phase scattering matrix radar data were developed which allow straightforward interpretation of polarimetric radar measurement data in terms of the characteristic geometrical and material features of isolated and distributed

targets. A new approach for dealing with partially coherent radar scatter was introduced by establishing a firm and transparent foundation for the Mueller-Stokes operator approach based on the coherency (density) matrix formulation of Emil Wolf for describing time-dependent canonical targets such as fluctuating dipoles, oscillating raindrops, ocean wave scatterers, etc., for purposes of target signal enhancement and clutter rejection under partially coherent conditions.

Using matrix optimization and group-theoretic approaches the properties of co- and cross-polarization nulls and maxima on the Poincaré sphere are established for the general multistatic cases. Based on the bistatic scattering matrix phenomenology, the objective of this research is to develop multistatic narrow-to-broad-band air-target/air-multipath (background reflection) target discrimination algorithms using complete polarimetric scattering matrix data. At high frequencies the electromagnetic scattering from a complex object is modeled by certain interactive scattering centers located on one and the same target and/or including one or more target-exterior multipath generated target image scattering centers. For this investigation, we are developing high frequency (physical optics) monostatic and bistatic scattering matrix plate models of such a scattering center. For these simple and other more complex scattering matrix model representations the single scattering center formulation is derived and then extended to two and three scattering center models. The bistatic scattering matrix for a multipath scattering problem, involving an isolated scattering center over an infinite plane reflecting surface has been derived. The difference between this case and the two scattering center model has been clearly demonstrated.

By analyzing these model scattering matrices, the electromagnetic inverse problem of recovering the high frequency scattering centers from multistatic polarimetric data is being investigated. Specifically, based on a knowledge of the location and the local geometries of these scattering centers, which can be recovered from multistatic scattering matrix data, the development of target classification, imaging, and identification algorithms have been advanced using novel polarimetric pattern recognition methods derived from the polarization null theory for the bistatic case.

The various developed target detection, classification, imaging, and identification algorithms are verified using polarimetric instrumentation radar data provided by various DOD/NASA (JPL) research radar instrumentation facilities. The obtained results are very promising and our research has now reached a more mature phase so that the established fundamental theories can be further advanced on a mission-oriented basic and exploratory developmental level.

I.3.2 Relevant Scientific Monographs/Special Issues/Workshop Proceedings Generated

The problem of radar target detection classification, imaging, and identification is closely related to electromagnetic vector inverse scattering/diffraction as described in

W-M. Boerner, "Polarization Utilization in Electromagnetic Inverse Scattering," Chap. 7 in Inverse Scattering Problems in Optics, H.P. Baltes, ed., Topics in Current Physics, Vol. 20, Springer 1980, New York, pp. 237-290 (also see: W-M. Boerner, ibid, UIC-EECS/CL Report, Oct. 1978)

W-M. Boerner, A.K. Jordan, and I.W. Kay (eds), IEEE Trans. A&P Special Issue on Inverse Methods in Electromagnetics, IEEE Trans. Ant. & Prop., Vol. AP-29, March 1981 (see introduction)

W-M. Boerner, et al. (eds), Inverse Methods in Electromagnetic Imaging

(Parts 1 & 2: 1347 pp), Proc. NATO-ARW-IMEI-1983, Sept. 18-24,
Bad Windsheim FRG, NATO-ASI Series C, Math & Phys. Sci. Vol. 143,
D. Reidel Publ. Co., Dordrecht/Boston, 1985

where the appropriate mathematical tools are identified and the physical interpretations are given, placing major emphasis on the polarimetric theory and the theory of partial coherence.

In order to solve the existing polarimetric radar target probing problems

- categorized in increasing order of complexity as:
perfectly conducting dielectric lossless/lossy/layered composite
dielectric/conducting isotropic/anisotropic target structure of
single to increasingly more complex shapes in isolation and or
distribution,

we must extend the known and well established optical inversion techniques, for example, such as ellipsometry, to the m-to-sub-mm wavelength region. For more rapidly (on a time scale of data acquisition) fluctuating targets, various background embediments such as meteorological, rough sea, and marine coastal scatter become important and dictate the use of coherent versus partially coherent approaches which differ from one spectral region to another.

Specific monostatic and bistatic radar modes of operation will dictate which particular metrological approach is required depending on the target/background spatial and motional properties including polarimetric pulsed versus FM-CW to polarimetric SAR imaging techniques. The resulting high resolution polarimetric downrange/crossrange and distributed scene measurement data formats then will dictate the development of novel multidimensional/multispectral polarimetric signal processing and polarimetric pattern recognition techniques as applied to target identification in severe and hostile clutter.

Although breathtaking advances have been accomplished in IR/optical systems and sensors, the multifunction multistatic/multispectral radar still provides and will for a long time to come, the most essential and important tool, in naval/ground/air and spaceborne military and civil operations which may be summarized by the following important features to which radar polarimetry will provide essential improvements:

- average (beyond the horizon) performance
- penetration of weather (fog, clouds, rain, severe storms, cyclones)
- range and doppler estimation
- flexibility due to electronic dual polarization beam steering
- various polarimetric and other vector signal processing routines
- high resolution polarimetric SAR imaging.

Different radar forms of operations such as target search, tracking, surveillance, fire control, and missile guidance can be strongly enhanced when combined with other multifunctional aspects such as multispectral, doppler, etc., which was well received in a recent NATO-AGARD Symposium to which our research team has provided strong input by invited papers as panel discussion contributions as identified in NATO-AGARD-CAP-381, Multifunction Radar and Airborne Applications, Avionics Panel Symposium, Toulouse France, 1985 Oct 14-18 (Proceedings uncl./class., published 1986). With increasing radar operating frequency, depolarization and diffraction effects become increasingly more important which requires a more advanced treatment including vector diffraction tomographic approaches and multispectral/multidimensional high-speed parallel processing computer implementations as was reviewed most recently in

W-M. Boerner, F.A. Molinet, and H. Überall, (eds), "Vector inverse methods

in radar target imaging," Proceedings of "Seminaire sur les methodes inverses vectorielles dans l'imagerie de cibles radar fouillis," Société Mothesim, SUPELEC, Gif-sur-Yvette, 1986 Sept 1-5, Springer Verlag, Topics in Current Physics, New York/Heidelberg, 1988, in preparation.

In this series of state of the art monographs the most effective scientific tools developed in a host of interdisciplinary physical fields of electromagnetic imaging are compiled, whereas a near-future NATO-ARW will be dealing exclusively with advancing the high resolution polarimetric radar target/imaging problem to be published in

W-M. Boerner et al. (eds), Direct and Inverse Methods in Radar Polarimetry, Proc. NATO-ARW-DIMRP (W-M. Boerner, Director), 1988 Sept. 18-24 Bad Windsheim FRG, NATO-ASI-Series C, (Math/Phys Sci), D. Reidel Publ. Co., Dordrecht/Boston, 1989.

I.3.3 Recent Results of Basic Radar Research

As a result of our computer-numerical investigations of the Huynen parameters and the questions raised about their validity, we have revisited the basic polarimetric radar theory dealing separately with the coherent and partially coherent cases as well as addressing the related vector (polarization) inverse scattering theories as was elaborated in all detail in

W-M. Boerner, A.B. Kostinski, B.D. James, M. Walther, D.W. Carnegie, A.P. Agrawal, B-Y. Foo, S.K. Chaudhuri, X-Q. Huang and N. Soliman, "Graphical Depiction of Targets Using Polarized Radar Data: Analysis of High Resolution Polarimetric Radar Downrange Signatures Using RCS Matrix Measurement Data Based on Kennaugh's Target Characteristic Operator and Huynen's Mueller Decomposition Theories," Final Report UIC-EECS/CL 1987-06-15, NADC, Contract No. N62269-85-C-0383, 1987 Sept. 11 (508 pages).

I.3.3.A Coherent Case

We have completed our analyses, assessing the fundamentals of radar polarimetry for the coherent case, as summarized in

A.B. Kostinski and W-M. Boerner, "On Foundations of Radar Polarimetry," IEEE Trans. A&P, Vol. AP-34, No. 12, Dec. 1986, pp. 1395-1404

H. Mieras, Comments "On Foundations of Radar Polarimetry," ibid, pp. 1470-1471

A.B. Kostinski and W-M. Boerner, Reply to Comments by H. Mieras, "On Foundations of Radar Polarimetry," ibid, pp. 1471-1473

in which we clearly identified crucial errors in the originating work of Kennaugh and Huynen; and in particular, to the incorrect definition of "polarization state" in

The IEEE Standard Test Procedure for Antennas, ANSI/IEEE Std. 149-1979 (Revision of IEEE Std. 149-1965),

which is being addressed in greater detail in

A.B. Kostinski and W-M. Boerner, "Formulation of Proper Standards in Radar Polarimetry," AMTA, Ninth Annual Meeting, Seminar 11, Seattle, WA, 1987, Sept. 28 - Oct. 2. (to be submitted to IEEE Proceedings, Feb. 1988).

In the latter paper we identified several crucial inconsistencies in the basic equations of radar polarimetry, which we found to be rather common in the past, recent, and current literature on the subject. In particular, we found the pertinent formulation of polarization state and the definition of the adopted formulation of receiver and transmitter antenna coordinate systems of the IEEE/ANSI-Std 149-1979 to be in error. A page-by-page analysis is provided in this reference with proposed revisions. Also pointed out are errors in the

respective formulations of Kennaugh and Huynen.

Employing the correct formulation of radar polarimetry, we have considered the problem of optimizing the "signal versus clutter-like" polarization ratio for the case in which scattering matrix element measurements can be obtained well below the "clutter decorrelation time" in terms of a purely coherent scattering matrix approach in

A.B. Kostinski and W-M. Boerner, "On the Polarimetric Contrast Optimization," IEEE Trans. A&P, Vol. 35, No. 8, pp. 988-991, August 1987.

Our approach complements and provides corrections to several previous optimization approaches, mainly given in the Russian literature.

Using the results of above papers, the target characteristic polarization null theory was reconsidered for the monostatic case in

A.P. Agrawal and W-M. Boerner, "Redevelopment of Kennaugh's Target Characteristic Polarization State Theory Using the Polarization Transformation Ratio Formalism for the Coherent Case," IEEE Trans. Geosci. (subm. Oct. 1986, resub. May 1987, acc. Feb. 1988).

Various null polarization plotting procedures are introduced and the limitations of the polarization ratio (ρ) formalism are being assessed against the more general three-stage procedure offered for the direct polarimetric optimization procedure in

A.B. Kostinski and W-M. Boerner, "On Foundations of Radar Polarimetry," IEEE Trans. A&P, Vol. AP-34, No. 12, Dec. 1986, pp. 1395-1404.

As relates to the Kennaugh coherent scattering matrix operator representation introduced by Huynen in terms of his five target characteristic parameters (target magnitude, m ; target characteristic angle, γ ; Eulerian target angles ψ , τ , ν), a more physically meaningful derivation is derived in the doctoral thesis

A. P. Agrawal, "A Polarimetric Rain Backscatter Radar Model for Coherent Polarization Diversity Radar Applications," Ph.D. Thesis, UIC-EECS/CL, University of Illinois, 1986 Dec. 15

and summarized in a recent publication

A. P. Agrawal and W-M. Boerner, "Description of Polarimetric Backscatter Model for Distributed Scatters for the Partially Polarized Case," Radio Science (subm. Oct. 1986, acc. May 1987)

utilizing high resolution polarimetric doppler $X/K_a/Q/W$ -band measurement data provided by MI-COM as reported in

W-M. Boerner, D.W. Carnegie, and A.P. Agrawal, "Monostatic Polarimetric (Scattering Matrix) Doppler Radar Backscatter Model for Rain," Final Report (428 pages), Battelle STAS-1597, (May 30, 1985 - June 15, 1986), Contract No DAAG29-81-D-0100, US Army MI-LAB, Redstone Arsenal, AL, 1986 June 15.

The important original studies of Kennaugh are contained in

D.L. Moffatt and R.J. Garbacz, "Research Studies on the Polarization Properties of Radar Targets," by Prof. Edward M. Kennaugh, The Ohio State University, Electro Science Laboratory, 1420 Kinnaer Rd., Columbus, OH 43212, July 1984, Vols. 1 & 2 (to be re-edited in Spring 1988).

Here we refer the reader to four of Huynen's major available publications:

J. R. Huynen, "Phenomenological Theory of Radar Targets," Doctoral Thesis, Technical University Delft, Delft, The Netherlands, 1970, Drukkerij Bronder-Offset N.V., Rotterdam, NL

J. R. Huynen, "Phenomenological Theory of Radar Targets," Ch. 11 in

Electromagnetic Scattering, Academic Press, N. Y. 1978 (ed. by P.L.E. Uslenghi: ISBN 0-12-7096, 50-7), pp. 653-712

J. R. Huynen, "A Revisitation of the Phenomenological Approach with Applications to Radar Target Decomposition," UIC-EECS/CL, Res. Rept. No.: EMID-CC-82-05-18-01, NAV-AIR-N00019-80-C-0620, May 18 1982

J. R. Huynen, "Towards a Theory of Perception for Radar Targets," (Sect. IV-2/RP 4, Part 2, pp. 797-822), in W-M. Boerner et al. (eds,) Proc. of the NATO Advanced Research Workshop on Inverse Methods in Electromagnetic Imaging, Bad Windsheim, FRG, 1983, Sept. 18-24, NATO-ASI, Series C, Math & Phys.Sci., Vol. 143, D. Reidel Publ. Co., Dordrecht, NL, Jan. 1985(2 parts).

However, there still exist very many open questions on the validity and utility of Huynen's five target characteristic parameters which can only be resolved after more insight into the partially coherent polarimetric radar problem is obtained. In our treatment of the coherent polarization radar case, we have also approached the extension to the nonreciprocal or bistatic transmitter-receiver configuration and particularly in

M. Davidovitz and W-M. Boerner, "Extension of Kennaugh's Optimal Polarization Radar Target Concept to the Asymmetric Scattering Matrix Data," IEEE Trans. on Antennas & Propagation, Vol. AP-34, No. 4, pp. 569-574, April 1986

in which it is shown that another two characteristic parameters, in addition to the five introduced by Huynen, are required to fully exploit the polarimetric properties of Kennaugh's target characteristic operator. Furthermore, in [Agrawal and Boerner, 1986] we have clearly shown that there exist, in general six optimal polarization states: a pair of co-pol. maxima being identical to a pair of cross-pol. minima, plus, a pair of co-pol. nulls. The cross-pol. maxima are not fully accounted for in Huynen's scattering matrix phenomenology. Major research investigations may still be required to resolve these fundamental issues.

1.3.3.B Partially Coherent Polarization Radar Theory

Although the downrange polarimetric target signatures to be investigated in this study were obtained with a coherent pulse compression radar system, the theory of partial polarization is relevant because we wished to investigate Huynen's Mueller matrix decomposition theory, which is supposedly based on the concept of partial coherence. We confidently say that Huynen's Mueller matrix decomposition theory was developed when the theories of partial coherence and partial polarization were still in a developmental phase. Therefore, Huynen's Mueller matrix phenomenology may require major revisions. In analyzing this problem of optimizing the contrast of partially polarized waves, we have come to the conclusion that hitherto no correct approach exists. We refer here to a very recent paper by the main contributor(s) to the theory of partial coherence.

K. Kim, L. Mandel and E. Wolf, "Relationship Between Jones and Mueller Matrices for Random Media," Journal Opt. Soc. Am. A, Vol. 4, No. 3, pp. 433-437, July 1987.

Here many existing misconceptions, including some of Huynen's are spelled out. Therefore, we embarked on an entirely new approach to the optimization of the Mueller matrix, i.e., the determination of the optimal Stokes vectors associated with a specific Mueller matrix for which there exist six vectors, in

A.B. Kostinski, B.D. James, and W-M. Boerner, "On the Optimal Reception of Partially Polarized Waves," J. Optical Society of America, Part A, Optics & Image Sciences, Series 2, Vol. 5, No. 1, pp. 58-64, Jan. 1988.

This does not agree with the optimal polarization states introduced by Huynen. In that paper the focus is on optimal intensity reception of partially polarized

waves scattered off a fluctuating object (ensemble of scatterers) of known polarization properties, the waves being expressed in terms of the measured Mueller matrix elements. Expressions for total available intensity as well as adjustable polarization-dependent intensity are derived in a clear and novel manner via the coherency matrix approach. We note that our results satisfy both the Barakat realizability condition and the Kattawar-Fry Mueller matrix inequalities, which are not identical with Huynen's inequalities as discussed in greater detail in our recent NADC Report. In a companion paper (in preparation), we treat the correct formalism of the Mueller Matrix Contrast Optimization based on a very fundamental revisitation of the Mueller versus Jones matrix concepts, and on a set of studies dealing with the physical realizabilities of the Mueller matrices in terms of [S] or Jones (bistatic) matrix time series. Finally, we are currently solving the polarimetric matched signal filter problem in light of a communication/information theory point of view, as well as the novel concept of the polarimetric matched (pixel) image filter concept.

Only after having resolved this set of basic problems, will we be able to properly address a methodological assessment of Huynen's phenomenologies as regards both the coherent and partially coherent cases.

I.3.4 Vector (Polarization) Inverse Scattering Approaches

In order to relate the polarimetric radar target signature with the geometric and material properties of the radar target, we have extended another important contribution of the late Professor Edward Morton Kennaugh, namely, his transient target ramp response analysis:

E. M. Kennaugh and D. L. Moffatt, "Transient Current Density Waveforms on a Perfectly Conducting Sphere (including complete list of related and other unclassified reports of late Prof. E. M. Kennaugh), pp. 1-31 (Part 1), W-M. Boerner et al. (eds.), Inverse Methods in Electromagnetic Imaging, Proc. NATO-ARW-IMEI, 1983 Sept. 18-24 (NATO ASI, Series C, Math & Phys. Sci., Vol. 143, Parts 1 & 2), D. R. Reidel Publ. Co., Dordrecht, NL, Jan. 1985.

This was done by applying his analysis to the bistatic polarization-dependent formulation presented in

B-Y. Foo, S.K. Chaudhuri, and W-M. Boerner, "A High Frequency Inverse Scattering Model to Recover the Specular Point Curvature from Polarimetric Scattering Matrix Data," IEEE Trans. A&P, Vol. AP-32 (11), pp. 1174-1178, November 1984

B-Y. Foo, S.K. Chaudhuri, and W-M. Boerner, "Extension of Kennaugh-Cosgriff's Formula to the Bistatic Case and Applications to Electromagnetic Direct and Inverse Scattering," IEEE Trans. A&P (subm. October 1986, acc. April 1987).

This vector inverse scattering theoretic approach was treated in the doctoral thesis

B-Y. Foo, "Application of Kennaugh's Ramp Response to Electromagnetic Vector Inverse Scattering in Monostatic and Bistatic Cases," UIC-EECS/CL, University of Illinois at Chicago, 1986 Dec. 15

and resulted in several relevant publications dealing with the inverse scattering model theory of recovering target specular point geometric and material parameters from scattering matrix measurement data. Especially, our high frequency electrical curvature model shows that the relative co-polarization phase $\frac{1}{2}(\phi_{HH} - \phi_{VV})$ is directly related to the difference in electric curvature $[(K_u - K_v)/k]$ at the specular point of a perfectly conducting smooth convex

scatterer given by

$$\left(\frac{\phi_{HH} - \phi_{VV}}{2} \right) = \pm \arctan \left(\frac{K_u - K_v}{k} \right)$$

We found this thesis to be of considerable use in interpreting Huynen's phenomenology, as described in

S.K. Chaudhuri, B-Y. Foo, and W-M. Boerner, "A Validation Analysis of Huynen's Target Descriptor Interpretations of the Mueller Matrix Elements in Polarimetric Radar Returns Using Kennaugh's Physical Optics Impulse Response Formulation," IEEE Trans. A&P, Vol. AP-34, No. 1, pp. 11-20, Jan. 1986.

This work is also of considerable importance to polarimetric SAR data interpretation as presented in

W-M. Boerner, B-Y. Foo, and H. J. Eom, "Interpretation of the Polarimetric Co-Polarization Phase Term in High Resolution SAR Imaging Using the JPL/CV-990 Polarimetric L-Band SAR Data," IEEE Trans. on Geoscience & Remote Sensing, Vol. GE-25, No. 1, pp. 77-82, Jan. 1987

where the utilization of both the polarimetric amplitude and relative polarimetric co-polarization phase term ($\phi_{HH} - \phi_{VV}$) of the scattering matrix [S], given pixel-by-pixel, was pursued for the first time for polarimetric SAR image interpretation.

The existing amplitude-only backscattering approaches hitherto used are extended and modified to accommodate the interpretation of information contained in the amplitude and/or phase terms of the returned signals. Both, a vector radiative transfer model for surface volume scattering from rough terrain with and without vegetation canopy, are examined in

H.J. Eom and W-M. Boerner, "A Re-Examination of Radar Terrain Backscattering at Nadir," IEEE Trans. Geosci. & Remote Sensing, Vol. GE-24, No. 2, pp. 232-234, March 1986

H.J. Eom and W-M. Boerner, "Scattering from a Layered Medium Connected with Rough Interfaces: Matrix Doubling Method," IEEE Trans. Geosci. & Remote Sensing, Vol. GE-24, No. 6, pp. 937-939, Nov. 1986.

The phase-difference identity derived from Kennaugh's basic PO ramp response identity represents a very important remote sensing identity in that it provides a first-order approximation on rough surface backscatter; i.e., whenever a (perfectly conducting) surface is flat, the relative co-polarization phase approaches zero, whereas for a "highly electrically curved surface (such as a corner reflector)" it approaches 180°. Provided look angles are increasingly off nadir and forward grazing angle, the above phase-difference approach cannot be applied, and another interpretation of the relative co-polarization phase term is required that can accommodate multipath phase difference contributions resulting from multipath effects along (semi) transparent layered media such as vegetated rough surfaces, sedimentary gravel/sand and/or hydrometeor stratifications. This latter problem is addressed in

S.K. Chaudhuri and W-M. Boerner, "A Polarimetric Model for the Recovery of the High-Frequency Scattering Centers from Bistatic-Monostatic Scattering Matrix Data," IEEE Trans. A&P, Vol. AP-35, No. 1, pp. 87-93, Jan. 1987

and

S.K. Chaudhuri and W-M. Boerner, "A Polarimetric Model for the Suppression of Multipath Ghost Images in Dual Polarization Real and Synthetic Aperture Radar Target Mapping Using Monostatic and Bistatic Scattering Matrix Data," IEEE Trans. A&P (subm. June 1987)

where great emphasis is placed on resolving multipath ambiguity problems in polarimetric RAR/SAR vertical stand-off remote sensing being directly relevant to this study.

1.3.5 Analytical & Probabilistic Radar Polarimetry Relevant to Polarimetric Radar (RAD/SCAT/RAR/SAR/ISAR) Development

In spite of a large amount of investigations and a recent tremendous upsurge of interest in polarimetric radar imaging, quite a few misconceptions still persist and several approaches lack in motivation in both basic and applied probabilistic radar polarimetry.

In basic polarimetry a critical distinction in the physical domains of validity of the coherent Jones scattering matrix [S] and the incoherent Mueller matrix [M] formalism has been severely undervalued. In fact, the NASA-JPL Pl. 86-29: Shuttle Imaging Radar-C Science Plan does not stress the very essential specification of the relevant time scale of the polarimetric measurements which are so crucial to the choice of the proper polarimetric formalism, as was discussed in detail in

A.B. Kostinski, B.D. James and W-M. Boerner, "Optimal Reception of Partially Polarized Waves," JOSA, A(Series 2), Vol. 5, No. 1, pp. 58-64, Jan. 1988.

regarding the applicability of either the Jones [S] or the Mueller [M] matrix formalism.

Even in the fast measurement regime, when the [S] formalism applies, the correct transformation rules versus receiver/transmitter decoupling and the determination of the $[G][S]^*[S]$ eigenvectors, identifiable as optimal polarimetric energy densities, must be introduced correctly. This was accomplished with the introduction of our three-stage procedure [Kostinski and Boerner, 1986] which also avoids critical errors in establishing the proper null mismatch polarization. In the slow measurement regime, on the other hand, one must ensure that the quantities optimized have a clear physical interpretation and significance. Simple formal and purely algebraic manipulations between [S] and [M] data will certainly not lead to new insights for geoscientific imaging, and the various recent studies we have seen lack physical understanding and intuition.

There has been less progress made in the statistical analysis of the polarimetric imaging data mostly because the statistical tools used are rather standard and do not take full advantage of the polarimetric character of the data as for example in [Ulaby et al., Jan 1987], or vice versa, when the polarimetric reasoning is not put into the relevant probabilistic setting of polarimetric imaging, a criticism that also applies to one of our own recent expositions on the meaning of the relative co-polarization difference term [Boerner, Eom, Foo, 1987].

Furthermore, there is a terrible lack in physical motivation displayed on the efficient and proper use of probability density functions for analyzing polarimetric radar/SAR imaging data, and, if used at all, they are typically introduced in a "rabbit out of the hat" fashion, e.g., Rayleigh, Gamma, Rice, Weibull functions, etc. Finally, it must be clearly pointed out that the statistical methods used on the "raw" polarimetric data observed recently in the literature and in NASA/JPL/DFVLR reports are not well suited for polarimetric signal/image and the vital problem of polarimetric speckle reduction can so not be addressed.

To overcome the above cited and other deficiencies of proper probabilistic handling of polarimetric image data, we have developed novel approaches to the problems along the following guidelines which are further backed up in

A.B. Kostinski, B.D. James, and W-M. Boerner, "The Polarimetric Matched Image Filter Concept in Radar Imaging," Canadian Journal of Physics Special

Issue on Optical Physics, INVITED, (sub. Jan. 1988, acc. May 1988, in print), Oct. 1988, Vol. 66, No. 10, pp. xx-yy),

using our novel and unique probabilistic optimal polarization interpretation methods applied to the polarimetric JPL/CV-990 C-band SAR data.

Based on our extensive analyses of various kinds of downrange/crossrange, holographic, and RAR/SAR/ISAR polarimetric (scattering matrix) imaging data, we are confident to state that our novel polarimetric matched signal/image filter approaches will rapidly advance the entire field of polarimetric SAR image analysis by considering:

- (1) Statistical analysis of physically significant polarimetric invariants, e.g., the span-invariant based on the raw scattering matrix elements and the importance of the span invariance, are discussed in the open literature for the first time in

W-M. Boerner, "Polarization Microwave Holography: An Extension of Scalar to Vector Holography," 1980 IOCC/SPIE Conference, 1980 April 9, Proc. No. 231-23, pp. 188-198.

and in

W-M. Boerner, "Imaging Radar Polarimetry" (invited base-lecture), JPL Workshop on Fundamental Research in Active Microwave Remote Sensing, JPL, Pasadena, 1982, Feb. 1-2.

The emphasis we are now basing on this identity, is on patch-by-patch terrain type analyses; implementing the use of the joint bivariate/multivariate probabilistic density function of $[S]$ elements must be stressed.

- (2) Re-examination of the existing literature on polarimetric radar/SAR treatments combined with our novel analytical studies with the goal of determining probability density functions most relevant for polarimetric geoscientific imaging are in urgent need. Clear physical interpretation of the dependence of physical parameters on the image structure and, in particular, deviation from Rayleigh-pdf behavior (the pure speckle image) must be stressed. Indeed, speckle contribution to the image statistics is often dominant and one must be "on guard" to distinguish between the "null polarimetric" dependence versus "cosmetic" changes due to, e.g., gray scale quantization, pixel discretization, etc. This approach has proven to become particularly promising for the construction of new algorithms in polarimetric speckle reduction.
- (3) The introduction of the Polarimetric Matched Image Filter is based on a combination of novel polarimetric approaches developed in our laboratory. First, we perform the polarimetric processing based on our three-stage procedure on a pixel-by-pixel basis, then investigate the joint density functions of the resulting $[S]^+ [S]$ eigenvectors, and finally we determine maximal and minimal average polarization, based on the multivariate pdf approach. In our current computer analysis of the NASA JPL C-Band POL-SAR image data, it is demonstrated that this novel approach provides maximal insight into the determination and interpretation of polarimetric responses of various image section categories, etc., and it clearly outperforms any other hitherto developed polarimetric feature enhancement methods.

Most important, subsequent simulation based on pdf peaks with the introduction of polarimetric matched image filter masks give a powerful new tool for sought image feature enhancement while, at the same time, enabling the suppression of undesirable speckle/clutter and natural/manmade obstructions (cloud cover, chaff, etc.).

- (4) Based on the above methods, we have also gained many deep insights into advancing various preflight/postflight electronic systems/recording/data processing calibration algorithms. The systematic investigation and development of these novel combined polarimetric SAR electronics/recording/processing system calibration procedures will become one of the main research tasks.

1.3.6 The Polarimetric Matched Image Filter Concept in High Resolution Radar

Imaging

Speckle reduction has long been recognized as the main problem of coherent imaging and many processing techniques have been advanced to overcome it. The vast majority of these techniques, however, are of scalar nature simply because vector/matrix imaging data are so sparse and have become available only very recently. We do have such data, which was taken with the NASA JPL/CV-990 dual-polarization L-band (1.225 GHz) SAR system. Therefore, our goal is to investigate the potential of an exclusively polarimetric image filtering approach, i.e., filtering which takes full advantage of the matrix data provided on a pixel-by-pixel basis and which complements the existing scalar speckle reduction techniques.

In a most recent submission

B.D. James, A.B. Kostinski, and W-M. Boerner, "Estimation and Enhancement of Polarimetric Features in POL-SAR Imaging with the Aid of the Polarimetric Matched Image Filter Concept," IEEE J. AES, (subm. Jan. 1988),

we have performed a statistical analysis of complete polarimetric SAR image data taken with the NASA JPL/CV-990 radar system. Eight real numbers (complex elements of the 2×2 polarization scattering matrix) are associated with each image pixel. This paper focuses on an ocean clutter removal based only on a polarimetric filtering approach, i.e., without the use of other image processing techniques. First, the optimal (maxima or minima of the digital or standard scattered power) transmitted and received polarizations are found for each image pixel according to our Three-Stage Optimization Procedure [Kostinski and Boerner, Dec. 1986] and then the results are analyzed statistically via a set of joint bivariate histograms of the eigenvectors implementing the six steps of the polarimetric matched filter procedure. Finally, the image response to the "optimal" antenna polarization is simulated digitally via the receiver polarization adjustment in accordance with relevant histogram peaks.

The great potential of complete polarimetric methods (i.e., scattering matrix utilization) for radar imaging has already been demonstrated by the JPL group using rudimentary outlines of introducing the polarimetric matched image filter concepts provided in

W-M. Boerner (INVITED), "Optimal Polarization Concept in Radar (RAD/SAR/RAR) Imaging," Proc. ESA-EAR Sd Workshop held in Alpbach, Austria, 16-20 March 1981 (ESA SP-166, May 1981, pp. 129-142).

Here, in our current studies, we have attempted to quantify and organize a search for optimal image contrast into a systematic polarimetric filtering method. This has been accomplished by combining our three-stage-procedure search for optimal polarizations on a pixel-by-pixel basis with a careful statistical analysis of polarization eigenvectors versus the terrain category and subsequent digital adjustment of the polarimetric variables E_T and h . We find the preliminary results very encouraging. We wish to emphasize here that the broad objective of the research is to establish a "tool-kit" of matrix image processing techniques, designed specifically for the polarimetric scattering matrix data handling on a pixel-by-pixel basis. Consequently, no effort is made to either model or interpret the polarimetric scattering patterns. This will be done in other forthcoming publications.

In order to improve the efficiency of the polarimetric filtering method, one must combine it with other image processing and statistical communication theory techniques. In particular, the filter efficiency depends sensitively on the histogrammic peak sharpness and one may employ block discretization, non-uniform quantization to improve the "peakedness" as discussed in

M. Walther, A.B. Kostinski, and W-M. Boerner, "Probabilistic Analysis and Some Polarimetric Signatures of POL-SAR Images," J. Geophys. Res., (subm. Aug. 1988).

Also, a continuous mapping in 3-color space of the three independent polarizations (say, HH, VV, VH) can be used in combination with the polarimetric matched filter to enhance visual detectability of the polarimetric terrain-type scattering dependence without destroying the geometric integrity of the image. Finally, an incoherent polarimetric imaging via the 4×4 real Mueller matrix may lead to an even more efficient speckle reduction procedure, in particular, for multilook images. All of these approaches are currently under investigation at the UIC-EECS/CL.

1.3.7 Polarimetric Doppler Radar Applications in Meteorology and Oceanography

Most recently, we were participating (Invited Panel Member) actively in a series of panel discussions on the technology of polarization diversity radars for meteorology, conducted by the American Meteorological Society at NCAR, Boulder, culminating in the Panel Reports of the

Battan Memorial and 40th Anniversary Conference on Radar Meteorology of AMS, 1987, Nov. 9-13, Boston, MA

of which Sessions 3.1 (Radar Meteorological Polarimetry), 3.2 (Mobile & Space Platforms), 3.3 (Polarimetric Signal Processing) are essential to this research and the resulting reports should be of eminent importance to the entire geoscientific research community utilizing polarimetric radar principles (ARO - Geosciences Division).

Coherent dual polarization doppler radars (CDPDR) have proven to be of paramount importance for the rapid advancement of theory and technique of remote sensing those environments in which the index of refraction is changing rapidly ($E \cdot \nabla \epsilon / \epsilon = \lambda / L$) and/or individual ensemble scatterer surface curvatures are very small compared to the radar operating wavelength ($E \cdot \nabla \sigma / \sigma = \lambda / L$), leading to pronounced polarization state transformations of the propagating and scattering waves such as encountered, for example, in radar meteorology and oceanography.

In each of the relevant radar bands L-to-W, different characteristic features of dynamically moving, turbulently mixing, and rapidly rotating hydrometeor ensembles can be studied with the use of such advanced CDPDRs and we need to acquire one for each band immediately, including both ground-based and spaceborne polarimetric radar and polarimetric SAR systems, respectively.

These aspects are reviewed in the Panel Report

V.N. Bringi and A. Hendry, "Technology of Polarization Diversity Radars for Meteorology," Session Report 3.1, Battan Memorial Conference, 1987, Nov. 9-13, Boston, MA (forthcoming in a Special Issue of the AMS Journal)

in our recent extensive study on Polarimetric Doppler Radar Meteorology

W-M. Boerner, D.W. Carnegie, and A.P. Agrawal, "Monostatic Polarimetric (scattering matrix) Doppler Radar Backscatter Model for Rain," Final Report, Contract No. DAAG29-81-D-0100 (Battelle STAS-1597), US Army MI-LAB, Redstone Arsenal, AL, 1986 June 15 (428 pages)

and the Ph.D. thesis of A.P. Agrawal (1987).

More recently, utilizing polarimetric doppler C-band measurement results

collected with the currently most advanced Coherent Dual Polarization (scattering matrix) Doppler Radar System operated by DFVLR Oberpfaffenhofen (Institutes of Atmospheric Physics and Radar Remote Sensing), it has been observed that the off-axis scattering matrix elements are not identical for those regions in electric storm formation in which very strong electrification prevails. This effect, combined with our finding from the evaluation of polarimetric doppler X/Ka/Q/V/W-band radar rain-backscatter data (MI-LAB/Boeing), in that the polarimetric doppler (quad) velocities can differ strongly for dynamically moving inhomogeneous severe storm formations, including, cyclones and ocean surface waves during high sea states, provide an entirely new motivation for utilizing POL-SAR data for specific spaceborne meteorological observations in addition to resolving the problem of range ambiguity (cloud top scatter versus ground surface scatter) using polarimetric radar methods.

In conclusion, it is safe to state that polarimetric doppler radar/RAR/SAR imagery from ground-based, airborne, and space platforms will become of paramount importance to radar meteorology and oceanography for the following reasons:

1. Using polarimetric doppler (scattering matrix) radar measurements one may be able to improve on or completely obtain:
 - (i) the local instantaneous/averaged vector of motion of turbulent dynamic hydrometeoric masses
 - (ii) more precise information on shape, velocity, and dynamic phase changes of hydrometeors within localized cloud regions
 - (iii) provide early detection of icicle/hailstones/etc., formation during initial hydrometeoric phase state changes
 - (iv) obtain more accurate estimates on cloud-water content, hail, precipitation, etc., which far outperform the currently adopted NEX-RAD system.
2. Using various different coherent polarimetric doppler radar systems such as DFVLR, SHAPE, DUT, etc., it is found that the scattering matrix in the polarization basis (H,V) is not symmetrical, i.e., $S_{HV} \neq S_{VH}$ (which seems to be a propagation rather than backscattering phenomenon). This effect will allow us to determine the anisotropic lattice structure created within electric storm clouds/precipitation regions and thus may provide a method for:
 - (i) predicting whether a cloud is electrically charged and possibly to which level,
 - (ii) predicting anomalous propagation effects within electric storm regions
 - (iii) predict severe hail and flash flood parameters.
3. Polarimetric Doppler Radar will enable:
 - (i) discrimination between fixed rigid targets versus strong turbulent (electric) storm clutter
 - (ii) distinction between various types of scattering centers including local vector of motion of non-uniformly moving and distributed dynamic scatterer ensembles such as rain, storm clouds, sea waves, vegetation canopies, etc.
 - (iii) will permit the identification of the local vector of motion (direction and amplitude) of wind shear.

4. Polarimetric (doppler) scattering matrix SAR imaging of distributed surface clutter (cloud tops of electric storm/tornado/hurricane systems, ocean surface, coastal surfzone, rocky terrain with and without vegetative canopy, vegetated areas, etc.) will greatly enhance target discrimination including detection of buried/sunken mines/submarines, etc.

In order to substantiate and further advance these important disciplines of Atmospheric Electricity, Electric Storm Systems Analysis, Tornado and Hurricane Research, Wind Shear Assessment, etc., it will be one of our main goals to utilize the SIR-C/X-SAR and other POL-SAR missions and request to receive those data sets which were collected over regions suffering from strong meteorologic and oceanographic storm conditions. Therefore, in collaboration with NCAR/Boulder, CO; NOAA-ERL-WPL/Boulder, CO; NOAA-ERL-NSSL/Norman, OK; NOAA-ERL-NHRL/Miami, FL; we are strongly engaged in pursuing the

Acquisition of Portable Coherent Dual Polarization (scattering matrix) Doppler Instrumentation Radar (CDFDR) Facilities in the L(1-2 GHz), S(2-4), C(4-8), X(8-12), K_u (12-18), K(18-27), K_a (27-40), Q(40-50), V(50-75), W(75-110 GHz) Bands for the Advancement of Radar Meteorology, Oceanography and Target in Clutter Handling for Ground-Based POL-RAD/SCAT, Airborne POL-RAR/SAR/ISAR and Spaceborne POL-SAR/SCAT Observations.

I.3.8 Terrain-Radar Backscattering Model for Spherical Waves

In the study of radar backscattering from naturally-occurring rough terrain, it is important to understand how the radio wave interacts with rough terrain. The scattered power, in general, consists of coherent and incoherent components, as discussed in

H.J. Eom and W-M. Boerner. "A Re-Examination of Radar Terrain Backscattering at Nadir," IEEE Trans. on Geoscience and Remote Sensing, Vol. TE-24, No. 2, March 1986, pp. 232-234.

The off-nadir backscattered power from rough terrain is mostly incoherent in nature due to the random structure of the terrain profile. The incoherent backscattered power strength is known to depend mostly upon rough terrain structures in terms of surface height, slope, and radar system parameters, including antenna beam width, operating frequency, and radar altitude. In the theoretical calculation of the incoherent backscattering coefficient, one often introduces the uniform-plane wave assumption for incident and scattered waves due mainly to its simplicity. The uniform-plane wave assumption allows one to approximate the actual spherical wave phase front as a planar one over the area illuminated by radar, thus, facilitating the scattering coefficient computation. One might suspect that the validity for the plane wave assumption seems to depend on the size of the illumination area relative to the surface height correlation length. The exact range of applicability for the plane wave assumption, however, remains quite ambiguous since many other factors, such as, antenna beamwidth, radar-altitude, frequency, and surface roughness may also be important in the radar backscattering process. This study is, particularly, of great importance in SAR imaging data calibration where the swath width across the track associated with azimuth Doppler processing is often large enough for the wave sphericity effects to be significant.

In order to model terrain structure, and its interaction with electromagnetic waves, one often adopts random rough scattering theories. Amongst many existing theories, we will use the Kirchhoff approximation and furthermore, for simplicity, assume that the rough terrain may be represented with a one-dimensional random rough Kirchhoff surface. In the next section, a theory regarding radar backscatter from a one-dimensional Kirchhoff surface is summarized and its theoretical angular behavior with a different choice of surface roughness is shown.

I.3.8.1 Incoherent Backscattered Power

In the Kirchhoff approximation, the incoherent backscattered power from a stationary Gaussian distributed random surface is given by

H.J. Eom and W-M. Boerner, "Incoherent Radar Backscattering for a Spherical Wave," in preparation.

Note that the effects of antenna beamwidth and sphericity are reflected in the backscattering coefficient.

The rough estimates for the relative importance of antenna beamwidth and sphericity can be obtained as follows:

- i) In case of a high altitude (airborne or spaceborne) radar, the condition $R_0 \beta_0 \gg 1$ may be easily met, where R_0 : range, β_0 : beamwidth, and λ : radar wavelength.

Hence, from the previous special case consideration, if the radar operates at a high altitude and the surface height correlation is small enough to satisfy the condition $1 \ll \lambda/\beta_0$, then the assumption of uniform plane waves for incident and scattered waves should be valid. In the comparison of incoherent radar backscattered power versus incidence angles between plane wave and spherical wave incidences, it is seen that due to the large beamwidth associated with the antenna, the actual radar backscattered power of a spherical wave exhibits much broader angular backscattering patterns as compared to the plane wave assumption.

The effects of antenna beamwidth and wave sphericity associated with the spherical wave are investigated using the one-dimensional Kirchhoff surface. It is found that the backscattering coefficients depends strongly on the beamwidth due to the effects of wave sphericity, in particular, in SAR imaging problems. It has also been shown that unless the surface correlation length l is much smaller than λ/β_0 , the plane wave assumption is invalid for scattering computations of randomly rough surfaces. The theoretical study indicates that the effects of antenna beamwidth must be accounted for in radar scattering computations of the L-band airborne/spaceborne SAR imaging radar and for systems operating at larger wavelengths.

I.3.9 Theoretical and Computational Advancements Toward Increased Image Fidelity in Microwave Vector Diffraction Tomographic Imaging

In this specific subtask we are addressing the inverse electromagnetic scattering and diffraction problem of refractive profile and conductivity reconstruction by EM wave probing and propagation through inhomogeneous media, as was recently summarized in

B.D. James and W-M. Boerner, "Toward Increased Image Fidelity in Microwave Diffraction Tomography," 1988 International Symposium on Radio Wave Propagation, Beijing, China, April 18 - 21, 1988.

We are especially paying major attention to the depolarizing terms in the wave equation which may be identified with the $(\vec{E} \cdot \nabla \epsilon)/\epsilon$ and the $(\vec{E} \cdot \sigma)/\sigma$ terms. These terms, commonly neglected, do produce appreciable effects if those become of the order of λ/L in magnitude, where λ is the probing wavelength in the media, L is the characteristic length of discontinuities, and ϵ and σ are the permittivity and conductivity, respectively.

Some of the theoretical and computational aspects of vector diffraction tomography in continuation of this research are presented in

B.D. James, "Vector Diffraction Tomography Using Radon Transform Techniques in Computer-Assisted Electromagnetic Imaging," M.Sc. Thesis, Jan. 1987,

and considered in

B.D. James and W-M. Boerner, "An Examination of Some Theoretical and Computational Aspects of Vector Diffraction Tomography," Inverse Problems, Int. Institute of Physics, Bristol, UK, (subm. Dec. 1987, resub. Fall 1988)

and

B.D. James, N. Soliman and W-M. Boerner, "The Effects of Data and Computational Errors in Vector Diffraction Tomography," JOSA, A(Series 2), (subm. Dec. 1987, resub. Fall 1988).

I.3.10 Application of Both the Polarimetric Radar/Lidar Matched Filter and Vector Diffraction Tomography to Vertical Standoff Surface Mine Detection

During the past two years, we have steadily refocused our research on multisensor polarimetric RAD/SAR/RAR/ISAR imaging to one of the still most complex unresolved military detection, surveillance, reconnaissance problems, namely that of detection of desirable targets such as mines in severe background clutter such as terrain, vegetation, coastal surface, and ocean marine environments. Inversely, we have also been very concerned with the problem of signature suppression at the radar, infrared, and visual wavelengths of the electromagnetic spectrum. For this purpose we have recently prepared two separate sets of solicited contract replies for the ARO/BRDEC and DARPA/BRDEC Broad Agency Announcements of Oct. 1986 and June 1987, respectively, entitled:

Lateral Standoff Imaging of Mine Perturbed Soils Using Vector (Polarization) Diffraction Tomography

Vertical Standoff Imaging of Mine Perturbed Soils Using Polarimetric RAD/SAR/RAR/ISAR Imaging Methods

Although we have not been granted a major contract award, we have been given a small research initiation project award under Contract Purchase Order BRDEC DAAK 70-87-P-2565, entitled:

Development of Vector Diffraction Tomographic Algorithms for Improved Image Fidelity in Electromagnetic Subsurface Object Imaging

which was based on the Lateral Standoff Imaging proposal outlines. During the recent five months, we have made very considerable progress on both approaches resulting in the analytical development and computer-numerical verification of the novel concept of the polarimetric matched signal/image filter technique for the strong enhancement of desirable target features and the effective reduction of surrounding clutter (also overburden) for which we require complete polarimetric (scattering matrix) measurement data. Currently, such coherent (2×2 scattering matrix [S]) and/or partially coherent (4×4 Mueller matrix) measurement data for coherent dual polarization illumination are not easily available. But, we have been fortunate to obtain various kinds of complete polarimetric radar data (NADC: target downrange/crossrange; NADC: ocean sea surface/coastal surf zone with and without targets; MI-COM: rain/vegetation scatter) as well as polarimetric SAR data (NASA/CAL-TEC JPL/CV-990 L-band POL-SAR). Using these valuable data sets, we were able to initiate our verification studies and to prepare a very detailed Solicited Contract Proposal Reply on behalf of UIC-EECS/CL to

NASA/NRA 87-OSSA-5, Polarimetric Analytical & Statistical Analysis of SIR-C/X-SAR Data Toward Determination of Optimal Polarization in Geoscientific Imaging, 1987 Nov. 30,

US Army BRDEC DAAK 70-88-Q-BHAI, August 1987, Application of Polarimetric Radar/Lidar Matched Filter Techniques to Vertical Standoff Surface Mine Detection, 1988 January 8,

US Army, MCOM-DAAH01-87-BAA, March 1987, Application of the PMSF/PMIF to Target Detection in Severe Dynamic Background Clutter, 1988 February

ARO, Basic Electromagnetic/Signal Processing Studies with Electronics/Geoscience/Signal Processing Applications to Geoscientific Problems in the 1GHz to 300 GHz Bands: Further Advancement of the PMSF/PMIF Concept, 1988 January 31

providing a very clear picture of what we are intending to achieve in the reorientation of our previous research based upon the integration of the "Polarimetric Matched Filter Technique with Diffraction Tomographic Approaches to POL-RAD/SCAT/SAR/RAR/ISAR" in various military and geoscientific applications.

1.4 ANTICIPATED RESULTS, IMPACTS, AND BENEFITS

1.4.1 Anticipated Results

The use of airborne/spaceborne ground-based imaging has become an essential tool of military surveillance and geoscientific remote sensing. In order to fully exploit the capabilities of electromagnetic vector (polarization) wave interrogation with the terrestrial boundary layer (coast, terrain/ocean surface, atmosphere, and troposphere), multi-frequency complete polarimetric scattering matrix radars in the L-to-W bands are in urgent need. Our past and current research has addressed this problem. We have been interacting very closely with DOD/NASA/NATO Research Centers involved in the planning and design of polarimetric radar sensors; discussing in great detail the urgent need for complete polarimetric (scattering matrix) radar development in order to recover maximum possible information on geoscientific remote sensing which is not possible by using only any one common/orthogonal transmit/receive polarization state such as, e.g., VV, HH, LL, LR, etc. Our research team at UIC-EECS/CL has been continuously involved in the struggle for the advancement of high resolution polarimetric (scattering matrix) radar imaging for geoscientific applications and in the detection/discrimination/classification/identification of hostile objects in natural and manmade speckle/clutter. Concurrent with this steep up-hill struggle, we have been able to strongly advance the fundamentals of radar polarimetry for the coherent and partially coherent cases. Most recently, with the use of complete (scattering matrix) polarimetric (doppler) downrange (single/double) to crossrange data of isolated targets, or targets embedded in various geophysical environments including bare and vegetated terrain with and without volumetric over/under-burden, ocean surface wave, and meteorological scatter from DoD (MI-LAB, NADC, NOSC/NWC), NATO-SHAP/TC, DFVLR, NTNF, RSRE, etc. With polarimetric SAR data from the late JPL/CV-990 (L-band) mission of the San Francisco Bay area, we have been able to develop novel and unique polarimetric matched image filter feature enhancement algorithms which at the same time, allow for the suppression of undesirable background speckle/clutter in airborne/spaceborne SAR.

It is our goal to build on the gained momentum and to further advance and sharpen the analytical, probabilistic, and computer-numerical/graphical tools of radar polarimetry, absolutely essential for developing optimal polarimetric SAR image interpretation for any and all applications. At the same time, it is also our goal to advance in our UIC-EECS/CL facilities specific interdisciplinary geoscientific image investigations dealing with significant feature enhancement and undesirable background speckle suppression essential to all military surveillance and geoscientific remote sensing applications.

Our research will benefit the entire military radar community by exhausting the polarimetric information content of the POL-RAD/SCAT/RAR/SAR/ISAR imagery using novel polarimetric matched image filter algorithms and polarimetric detection systems and post-processing data calibration. Specifically, we will be able to extract and compare probabilistic densities of optimal polarizations character-

istic of specific terrain-oceanographic surface and/or meteorological top-surface scatter with applications to the determination of (i) rock surface features and texture decomposition of various areal sizes; (ii) of volumetric under/over-burden versus surface backscatter; (iii) localized oceanwave wind vector (ampl & direction); (iv) spaceborne detection/tracking/classification of hostile objects (military targets) in a sensitive geophysical environment (polar/subpolar regions & packice, vegetated coastal surf zones, tropical forests, etc); and (v) water content and electrification of severe storm cloud formations and cyclones.

I.4.2 Merits

Hitherto, sufficient emphasis was not placed in utilizing the complete polarimetric (scattering matrix) RAD/SAR/RAR/ISAR signatures in extracting optimal information about target versus clutter. In fact, only partial polarimetric information was utilized, thus leading to gross misconceptions about the real benefits of polarization utilization in target detection and camouflage problems. In our novel polarimetric matched image filter technique, combined with tomographic image enhancement, the most complete electromagnetic target versus clutter discrimination can be achieved to yield improved high resolution electromagnetic imaging applicable to target and mine detection.

I.4.3 Benefits

In summary, the full understanding of the electromagnetic wave/target interrogation capability, as the polarimetric doppler radar/SAR (subject to $S_{HV} = S_{VH}$ not being a design requirement) will provide, is of paramount importance to the analysis of the complete radar wave interaction with the ground terrain, the ocean surface, and/or the meteorological surface cover in that it will provide us with the essential key as to how we may maximally extract hard-to-delineate scatterer features of isolated and/or combined objects, etc. The types of analytical rough surface and vector inverse scattering studies in conjunction with the polarimetric radar/SAR data analysis currently conducted with already available data sets and proposed for various POL-RAD/SCAT/SAR/RAR/ISAR analyses will be extremely helpful to all other geoscientific disciplines and, in particular, for the earth sciences including geology, hydrology, glaciology, and oceanography; and in biospheric, cryospheric, and atmospheric remote sensing. Indeed, this highly improved understanding of microwave (L-W band) polarimetric (scattering matrix) interaction with targets and clutter will allow us to process the polarimetric radar data in a more meaningful, straight-forward manner for maximal target enhancement and optimum speckle suppression without taking recourse to electromagnetically unjustified statistical (arbitrary:geo-electromagnetically) multiple parameter data adjustment games.

I.4.4 Socio-Economic Impact

In combination and complementation with other participating team efforts our novel and unique polarimetric matched image filter approach will lead to:

- (i) more efficient surveillance, control, and tracking of geophysical resources within the very fragile terrestrial environment such as the polar/subpolar, vegetated coastal surf zones, and tropical forestal regions
- (ii) improved short term (immediate) and long term weather forecasting integrating spaceborne high resolution polarimetric doppler SAR imagery of localized severe electric storm/tornado and/or global dynamic cyclonic motions, respectively; also, improving on tornado/cyclonic tracking and damage impact predictions
- (iii) advancement of electro-optical polarimetric radar device technology with wide applications in military and space radar development for

planetary exploration or, closer to earth, for on-board aircraft collision avoidance and more precise instantaneous electric storm/downburst (lower frequencies) prediction and tracking.

I.5 LIST OF TECHNICAL REPORTS AND INTERACTION NOTES

I.5.1 Semi-Annual Progress Reports for ARO Proposal No. 22207-EL/Contract No. DAAC 28-85-K-0065 (not attached)

- I.5.1.1 Contract Initiation Date: 1985 February 28; Proposal Submission Date: 1984 May 01; Proposal Acceptance Date: 1985 Jan. 04
- I.5.1.2 Semi-Annual Progress Report: 1985 July 15; Period: 1985 Jan. 01 to 1985 June 30
- I.5.1.3 Semi-Annual Progress Report: 1986 January 31; Period: 1985 July 01 to 1985 Dec. 31
- I.5.1.4 Semi-Annual Progress Report: 1986 Sept. 30; Period: 1986 Jan. 01 to June 30
- I.5.1.5 Semi-Annual Progress Report: 1987 Jan. 31; Period: 1986 July 01 to 1986 Dec. 31
- I.5.1.6 Semi-Annual Progress Report: 1987 July 25; Period: 1987 Jan. 01 to 1987 June 30
- I.5.1.7 Semi-Annual Progress Report: 1988 Jan. 15; Period: 1987 July 01 to 1987 Dec. 31
- I.5.1.8 Semi-Annual Progress Report: Final Report; Period: 1988 Jan. 01 to 1988 Aug. 2

I.5.2 Foreign Travel Reports (Available Upon Request)

- I.5.2.1 W-M. Boerner, 1985 August 12 to September 7, Pacific NW Research/Symposium Interaction Travel (1985 Oct. 14): ISAP '85, Kyoto; ISAE '85, Beijing, and NPU-XIAN Workshop
- I.5.2.2 W-M. Boerner, JSPS CAST US Senior Scientist Fellowship Japan/China Research Travel Report (1986 August 15): Advancement of Science & Technology in High Resolution Radar Polarimetry Using Electromagnetic Inverse Methods, Phase I: 1986, March 23 to 1986 July 23
- I.5.2.3 W-M. Boerner, Report on Sabbatical Research Leave as Alexander von Humboldt US Senior Scientist Fellow Award (1988 May 31): The Advancement of Inverse Methods in High Resolution Polarimetric Target Imaging in an Air/Land/Sea Clutter Environment, WQ/SQ-87: 1987 Jan. 01 to 1987 July 31
- I.5.2.4 W-M. Boerner, JSPS/CAST US Senior Scientist Fellow Award (1988 May 31): Advancement of Science & Technology in High Resolution Radar Polarimetry Using Electromagnetic Inverse Methods, Phase II: 1988 March 14 to 1988 April 30.
- I.5.2.5 W-M. Boerner, Special Confidential Report: Thought Provoking Observations Made During Recent Research Visits to Japan and PRC (Not for distribution outside DOD), 1988 May 31, prepared for ONR/ONT, Arlington, VA, Codes 111, 113 and Task Force 168.

I.5.3 Major (Final) Technical Research Reports (Not attached)

- I.5.3.1 W-M. Boerner, A.B. Kostinski, et al., Stationary Target Detection/Classification Algorithm Development Applied to Armored Vehicle Detection in Ground/Tropospheric Clutter, Final Report, 1985 Oct. 14, US Army Res. Office/ US Army Lab Command, Harry Diamond Labs, Radar Physics Sect., Contract No. DAAK 21-84-C0101 (Solicitation DAAK 84-R-9150), Dept. No. UIC-EECS/CL: ARO/HDL 85-10-14

I.5.3.2 W-M. Boerner, D.W. Carnegie, and A.P. Agrawal, "Monostatic Polarimetric (scattering matrix) Doppler Radar Backscatter Model for Rain," Final Report, Contract No. DAAG29-81-D-0100 (Battelle STAS-1597), US Army MI-LAB, Redstone Arsenal, AL, 1986 June 15 (428 pages)

I.5.3.3 W-M. Boerner, A.B. Kostinski, B.D. James, M. Walther, D.W. Carnegie, A.P. Agrawal, B-Y. Foo, S.K. Chaudhuri, X-Q. Huang and N. Soliman, "Graphical Depiction of Targets Using Polarized Radar Data: Analysis of High Resolution Polarimetric Radar Downrange Signatures Using RCS Matrix Measurement Data Based on Kennaugh's Target Characteristic Operator and Huynen's Mueller Decomposition Theories," Final Report UIC-EECS/CL 1987-06-15, NADC, Contract No. N62269-85-C-0383, 1987 Sept. 11 (508 pages).

I.5.3.4 Internal Technical Interaction Notes

Alexander B. Kostinski, #ABK-1,
March 14, 1985

"Unitary Matrix Formalism and the Optimal Polarization Concept in Radar Scattering Theory"

Alexander B. Kostinski, #ABK-2,
March 14, 1985

"Optimization of the Bilinear Voltage Form in the Monostatic and Bistatic Radar Image Arrangements - Including Explicit Construction of the Diagonalizing Unitary Matrices"

Alexander B. Kostinski, #ABK-3,
March 13, 1985

"Possible Real Time Applications of the Voltage Optimization: Real Time Feasibility Analysis"

Alexander B. Kostinski, #ABK-4,
April 14, 1985

"Careful Derivation of the Received Voltage Equation and the Scattering Matrix Change-of-Basis Transformation Formulation"

Alexander B. Kostinski, #ABK-5,
April 14, 1985

"On Various Polarization Mappings Used in Radar Polarimetry"

Alexander B. Kostinski, #ABK-6,
May 14, 1985

"Informal Tutorial Notes on the Mathematics Fundamentals to Radar Polarimetry: Linear Algebra and Canonical Targets in a Linear and Circular Polarization Basis"

Alexander B. Kostinski, #ABK(WMB)-7,
June 15, 1985

"On Foundations of Radar Polarimetry: Part I - Coherent Case"

Alexander B. Kostinski, #ABK(WMB)-8,
August 14, 1985

"A Critical Review of the Target Characteristic Operator (Polarization Fork Concept)"

Alexander B. Kostinski, #ABK(WMB)-9
September 14, 1985

"Corrections to the IEEE Standards: Test Procedures for Antennas" ANSI/IEEE Std. 149-1979, pp. 76-88

Alexander B. Kostinski, #ABK(WMB)-10
October 14, 1985

"Assessment of Huynen's Approach to Radar Target Phenomenology in Relation to Recent Advances in Fundamentals of Radar Polarimetry"

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| Alexander B. Kostinski, #ABK(WMB)-11 November 14, 1985 | "Rebuttal to #ABK-7: Overall Response to the Comments of the Reviews and the Editor" |
| Alexander B. Kostinski, #ABK(WMB)-12 December 14, 1985 | Re-Edited, Reduced Version of #ABK-7, "On the Foundations of Radar Polarimetry" |
| Amit P. Agrawal, #APA(WMB)-1 April 14, 1985 | "Derivation of Null Polarizations Using the Unitary Transformation Matrix in Terms of the Polarization Ratio ρ and Their Interpretation on the Poincaré Sphere" |
| Amit P. Agrawal, #APA(WMB)-2 May 14, 1985 | "Analysis of Characteristic Properties of the Null-Polarization States Derived from the Power (Graves) Scattering Matrix and the Graphical Mapping on the Poincaré Sphere" |
| Amit P. Agrawal, #APA(WMB)-3 July 14, 1985 | "Monostatic Polarimetric Radar Backscatter Model for Rain: Critical Literature Review for Monostatic Polarimetric Precipitation Clutter Models" |
| Amit P. Agrawal, #APA(WMB)-4 July 14, 1985 | "Development of a Model-Free Clutter Backscattering Theory Based on the Coherency/Mueller Matrix Approach" |
| Bill Xiao-Qing Huang, #XQH(WMB)-1 May 15, 1985 | "Mercator Conformal and Lambert, Mollweide, Aitoff-Hammer Equal Area Projections of the Polarization Sphere and Their Applications to Radar Polarimetry" |
| Bing-Yuen Foo, #BYF(WMB)-1 July 15, 1985 | "Basic Monostatic Polarimetric Broadband Target Scattering Analysis Required for High Resolution Polarimetric Radar Target Downrange/Crossrange Imaging of Airborne Scatterers" |
| Bing-Yuen Foo, #BYF(WMB)-2 October 14, 1985 | "Interpretation of Kennaugh's Physical Impulse Response Approach for the Slightly Bistatic Case" |
| Bing-Yuen Foo, #BYF(WMB)-3 January 6, 1986 | "Extension of Kennaugh's Transient Target Ramp Response Concept of Lossless Homogeneous Dielectric Scatterers" |
| Brian D. James, #BDJ-1 | "Development of Tensorial Diffraction Tomography for Electromagnetic Imaging Through Inhomogeneous Media at Meter-to-Millimeter Wavelengths" |
| Ali M. Khounsary, #AMK(HJE)-1 August 14, 1985 | "A Discrete Vector Radiative Transfer Formulation of Multiple Scattering Problems in Multi-Dimensional (Plane-Parallel) Media Using a Method of |

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| | Adding/Doubling of Discrete Cubes (Layers)" |
| Vithal K-S. Mirmira, #VKSM(WMB/KU)-1 December 14, 1985 | "A Critical Assessment of the Target Complex Natural Resonance Descriptors" |
| Sheng-Ming Huang, #SMH(WMB)-1 December 14, 1985 | "Application of Kennaugh's Polarization Corrected Inverse Scattering Identity to Radar Target Shape Reconstruction" |
| David W. Carnegie, #DWC(WMB)-1 November 14, 1985 | "Spectral Analysis of Radar Scattering Matrix Time Series for MI-COM Rain Scatter Data" |
| David W. Carnegie, #DWC(WMB)-2 November 31, 1985 | "Correlation Functions for Target Recognition Applied to NADC/Teledyne High Resolution Downrange Scattering Matrix Data" |
| David W. Carnegie, #DWC(WMB)-3 December 14, 1985 | "Rayleigh/Mie Scattering and the Polarizability of Raindrops in the Monostatic/Backscatter Case" |
| Jonas O. Okeke, #JOO(HJE)-1 December 14, 1985 | "A Simple Empirical Model for Near-Grazing Sea Radar Backscattering" |
| Alexander B. Kostinski, #ABK(RAC/WMB)13 December 31, 1985 | "Investigation of Radar Target Detection Techniques in Turbulence for the Sub-Millimeter Wavelength Region" |
| Robert M. Lempkowski, #RBL(WMB)-1 October 31, 1985 | "A Modular Testbed Design of a High Resolution Polarization Radar for Target in Clutter Detection and Description" |
| Matthias Walther, #MW(WMB)-1 November 14, 1985 | "Assessment of Polarimetric Millimeter Wave Sensors in the Design of Airborne/ Marine Ground Vehicle Collision Avoidance and Traffic Flow Control Radars" |

I.6 SUMMARY OF RESEARCH INTERACTIONS

(No detailed day-to-day records are presented here because they are contained in the Semi-Annual Reports)

I.6.1 Visits to DOD-Facilities

Continuous interaction took place with research contract officers, research scientists, and engineering personnel of the DOD (ARMY, NAVY, AIR FORCE AND MARINES) Facilities listed in the Distribution List of Section I.11. (No further details are provided here, but are recorded in the Semi-Annual Reports).

I.6.2 National Radar Consulting Services

1980- : DRSMI-REG, Millimeter Guidance Technology, Advanced Sensors Directorate, US Army Missile Command, Redstone Arsenal, AL (m-to-mm-wave near-to-ground, polarimetric clutter analysis).

1982-1985: Schlumberger-Doll Research, Electrical Engineering Department, Ridgefield, CT. (geophysical inverse methods VSP).

1982-1986: Raytheon Company, Missile Systems Division, Bedford, MA. (radar polarimetry).

1982-1986: Boeing Aerospace Co., RF Sensors Lab, Engineering Technology Division, Seattle, WA (radar polarimetry).

1982-1984: Scientific Atlanta, Radar Cross Section Measurement Division, Atlanta, GA. (development of bistatic radar cross section matrix measurement ranges).

1982-1984: Bendix Corporation, Guidance Systems Division, Teterboro, NJ (radar polarimetry).

1982-1985: Enterprise Electronic Corporation, Radar Meteorology Division, Arlington, VA (radar polarimetry).

1983- : General Dynamics, Convair Division, San Diego, CA (radar polarimetry).

1983-1985: Martin Marietta, Orlando, FL (radar polarimetry).

1983- : General Dynamics, Pomona Division, Pomona, CA (radar polarimetry).

1983- : TRW, Inc., Defense & Space Division, Manhattan Beach, CA (radar polarimetry).

1983-1985: Battelle Columbus, Research Triangle Park, NC (radar meteorology)

1983- : Westinghouse, Friendship International Airport, Baltimore, MD (radar polarimetry).

1983- : Scientific Atlanta, Instrumentation Division, Atlanta, GA (radar polarimetry).

1983- : Eglin Air Force/AFATL-DLMT, Eglin AFB, FL (radar polarimetry).

1983-1985: Boeing Military Airplane Co., Wichita, KS (radar polarimetry).

1984-1986: Honeywell, Aerospace & Defense Group, Systems Research Center, Minneapolis, MN (radar polarimetry).

1984-1986: Hughes Aircraft Company, Space & Communications Group, Space Sensors Laboratory, El Segundo, CA (radar polarimetry).

1984- : General Electric Co., Military Electronics Systems, Advanced Development Engineering, Syracuse, NY (radar polarimetry).

1984-1986: Honeywell, Defense Systems Group, Millimeterwave Radar Signature Group, Attn: Dr. James Marier (polarimetric radar imaging).

1984-1986: Honeywell, Systems & Research Center, Radar Signals and Imaging Division, 2600 Ridgway Parkway, Minneapolis, MN 555413, Attn: Dr. Raja Suresh (polarimetric SAR imaging).

1984 : Sandia National Laboratories, E.M. Division, Albuquerque, NM, (Radar Polarimetry and Radar Target Identification).

1984-1986: U.S. Air Force AFSC RAT-SCAT, 6585th Test Group/RX Whitesands Missile Range, Holloman AFB, N.M. 88330, Attn: Mr. Stanley D. Shaw, Technical Director (505) 679-3110/3120 (radar polarimetry).

1984-1986: Dynallectron, Corp. RAT-SCAT/RX P.O. Drawer O, Holloman AFB, NM 88330, Attn: Stanley A. Guy (505) 679-3180 (radar polarimetry).

1984-1986: Dynallectron, Corp. Advanced Radar Signatures Division, P.O. Drawer 1, Alamogordo, N.M. 88310, Attn: Mr. James Lutz, (505) 434-3525/3630 (radar polarimetry).

1985-1987: Epsilon Lambda Electronics Corp., Millimeter-wave Radar Div., 427 Stevens Street, Geneva, IL 60134 Attn: Mr. Robert Knox,

- President (312) 232-9611 (radar polarimetry).
- 1985-1986: Millimeter Wave Technology, Inc. P.O. Box 19678, Atlanta, GA 30325, Attn: Dr. James W. Schuchardt (404) 892-0710 (radar polarimetry)
- 1985- : Global Analytics, San Diego, CA, Attn. Dr. S. Weisbrod (radar polarimetry).
- 1986- : The Johns Hopkins Univ., Applied Physics Lab., Laurel, MD (polarimetric radar target in sea-clutter discrimination).
- 1987- : Battelle Memorial Columbus (US Army MI-Lab), Research Triangle Park, NC (radar meteorology).
- 1987- : Battelle Memorial Columbus (Ft. Belvoir: BRDEC), Research Triangle Park, NC (electromagnetic sounding/counter mine).

I.6.3 NATO/MOD Interactions

SHAPE-TC on High Resolution Polarimetry, The Hague, Dec. 1983, May 1984, Oct. 1985, Feb. 1986, April 1987, Dec. 1987.

NATO Advanced Science Advisory Board Meeting at SHAPE Headquarters, Mons, Belgium on September 1983, December 1984, May 1985, Feb. 1986, Sept. 1986, Jan.-July 1987, Dec. 1987.

DFVLR-Oph. on High Resolution Radar Polarimetry and Polarimetric Radar Meteorology on Sept. 1983, Dec. 1984, May 1985, Feb. 1986, Sept. 1986, Dec. 1987.

Royal Signals & Radar Establishment, Ministry of War & Defense, Great Malvern, U.K., on "High Resolution Polarimetric Radar Target Imaging," Oct. 1984, Oct. 1985, April 1987.

Ministry of Science & Technology/Ministry of Defense, Bonn, FR Germany, Invited Specialist Research Lecturer on Advanced Radar Technology on Sept. 1983, Dec. 1983, May 1984, Dec. 1984, May 1985, Sept. 1986, Feb. 1987, April 1987, Dec. 1987.

NATO-Scientific Affairs Division, Brussels, Final Rept. on NATO Advanced Research Workshop on Inverse Methods in Electromagnetic Imaging, Dec. 1983, May 1984, Oct. 1985, Sept. 1986, April 1987, Dec. 1987.

TNO, Netherlands Technology National Office, Dept. of Defense, NL., on High Resolution Polarimetric Radar Target Imaging in Land and Sea Environments, Dec. 1983, May 1984, Dec. 1984, May 1985, Sept. 1986, April 1987, Dec. 1987.

FRG, Military Institute of Technology, Hamburg, on High Resolution Radar Polarimetry, Dec. 1983, May 1984, May 1985, May 1986, May 1987.

The U.K. Admiralty Research Establishment Ministry of War & Defense, Coshan/Portsmouth, U.K., Development of High Resolution Polarimetric Radar Target in Clutter Distribution/Classification for a Marine Environment, Oct. 1984, April 1987.

NTNF, Royal Norwegian Defense Council of Research, Surveillance Radar & Remote Sensing Division, Kjeller, Norway, May 1984, Sept. 1986, Feb. 1987, March 1987, April 1987, May/June 1987, July 1988.

ONERA, French Defense Space Research Establishment, Chatillon-Bagneux, France, Sept. 1986, May 1987.

FRG-WEHRTECHNIK Seminar, BONN, FRG, Feb. 1987.

AWI-Alfred Wegener Institute for Polar Research, Bremerhaven, FRG, Feb. 1987.

Max PLANCK Institute for Meteorology, Hamburg, FRG, Feb. 1987.

FGAN, IHFP/IMM, WACHTBERG-Werth-hoven, FRG, Sept. 1986, Feb. 1987.

FGAN, Inst. of Optics, Tübingen, March 1987.

Royal Dutch Inst. of Meteorology, de Bilt-Utrecht, April 1987.

AEG-Telefunken, Ulm, FRG, May 1984, May 1985, Feb. 1986, Feb. 1987, April 1987, Dec. 1987.

Siemens-Radar Electronics Division, Munich, FRG, Dec. 1983, May 1984, Feb. 1986, Sept. 1986, March 1987, Dec. 1987.

Rohde & Schwarz, Military Electronics Division, Munich, FRG, May 1984.

Dornier Aerospace Corp. Friedrichshafen, FRG, May 1984, March 1987.

Standard Elektrik Lorenz, Stuttgart, FRG, May 1984, September 1984, December 1984, May 1985, Sept. 1986, Feb. 1987, Dec. 1987.

Selenia, Florence, Italy, Aug. 1984, May 1987, Dec. 1987.

CARL ZEISS, OBERKOKEN, FRG, March 1987, Dec. 1987.

Messerschmidt-Bölkow-Blohm, Ottobrunn/Neubieberg, FRG, Sept. 1984, Feb. 1986, April 1987, Dec. 1987.

Thorn-EMI, Wells, Somerset, UK, Oct. 1984.

Contraves (GmbH), Bein, Switzerland, April 1987.

Tompson-CSF, Malakoff-Paris, Oct. 1985, Sept. 1986, Feb. 1987, May 1987.

MATRA, Space Radar Division, Toulouse, France, Oct. 1985, May 1986, June 1987.

Aerospatiale, Radar Division, Toulouse, France, Oct. 1985, Sept. 1986.

DIEHL (GmbH), Nuremberg, FRG, Dec. 1983, May 1985, March 1987, Dec. 1987.

Ericson, Radar Division, Göteborg, Sweden, Feb. 1987.

1.6.4 Japanese Industries

"The Electromagnetic Inverse Problem and High Resolution Radar Target Imaging", Toshiba RDE Center, Kawasaki, April 18, 1986.

"Radar Polarimetry and Satellite Remote Sensing", Mitsubishi (Kamakura/Ofuna works), Kamakura, April 18, 1986.

"Electromagnetic Inverse Problems", Nippon Telegraph & Telephone Co., Yokosuka, Electronics Commu. Lab., April 23, 1986.

"Optical Inverse Problems and High Speed Opto-Electronic Signal Processing", The Furukawa Electric Co., Chiba, April 24, 1986.

"Optical and Millimeter-wave Precision Imaging Using Electromagnetic Inverse Methods", Suzuki Motor Co., Kosai Plant, Shizuoka, May 1986.

"Polarization Perception by Insects, Fish, Eel, Birds, Mammals and Man", The Japan National Institute for Physiologic Electronic Sciences, Okazaki, May 9, 1986.

"Use of Millimeter-Wave Radar in Traffic Control", Honda Electronics Research Center, Toyohashi, May 13 (am), 1986.

"High Resolution M-to-MM-Wave Imaging", Riken EM (Absorbers) Inc., Nagoya, May 13 (pm), 1986.

"The Electromagnetic Inverse Problem and High Resolution (Precision) Imaging in the m-to-sub-mm Wavelength Region", Toyota Research Laboratory, Nagakuto, Aichi, May 14 (am), 1986.

"Applications of Electromagnetic Imaging Methods to Design of Millimeter Precision Robot Control in Automation", Brothers Industries, Mizukoku, Nagoya, May 14 (pm), 1986.

"Electromagnetic Imaging of Underground Obstacles", NCC Musashino Research Laboratory, Musashino, May 28, 1986.

"High Resolution Polarimetric Radar Imaging", Nippon Electric Company, NEL Space Development Division, Yokohama, May 29, 1986.

"High Resolution Polarimetric Radar/Lidar Imaging", Furukawa Electric Co., Opt. Fiber/Integrated Circuits Division, Chiba, June 17, 1986.

"Use of Millimeter-wave Radars in Traffic Flow Control", Hitachi Central Research Laboratories, Kokubunji, Tokyo, June 19, 1986.

I.7 PUBLICATIONS

I.7.1 Editorships

IEEE, Antennas & Propagation Society, Transactions, **Associate Editor** (Inverse Methods and Imaging), January 1980 to December 1986.

IEEE, Transactions Antennas & Propagation, Vol. 29(2), 1981 Special Issue, Inverse Methods in Electromagnetics, **Guest Editor**, 1980-1981, (417 pages), PR.

NATO Advanced Research Workshop on "Inverse Methods in Electromagnetic Imaging", September 18-24, 1983, Proceedings, **Chief Editor**, 1982-1984, (1400 pages), D. Reidel Publ. Co., Jan. 1985, PR/B.

Royal Society of Physics (UK), Journal of Physics, Section E, (new: First International) Inversion Methods in the Physical Sciences, **Associate Editor** (electromagnetic/vector), December 1983 to Dec. 1988.

SOC-MOTH (NATO), Advanced Research Short Course, Vector Inverse Methods in Radar Target/Clutter Imaging, Co-Editors (W-M. Boerner, F.A. Molinet, H. Überall), Proceedings, ARSC, Ecole Supérieure d'Electricité, Gif-sur-Yvette, France, 1986, Sept 1-4, Springer Verlag, Heidelberg, 1988, total pages: 428. PR.

NATO, Advanced Research Workshop on "Direct and Inverse Methods in Radar Polarimetry", Sept. 18-24, 1988, Proceedings, **Chief Editor**, 1987 - 1989 (1,500 pages), D. Reidel Publ. Co., Dordrecht, NC, exp. 1989/1990, PR.

W-M. Boerner and A.B. Kostinski (**book authors**), Introduction to Radar Polarimetry, John Wiley & Sons, Research Studies Press (J.R. Jones, Series Editor), Englewood Cliffs, N.J., 1988 (360 pages): in preparation, B.

W-M. Boerner and B-Y. Foo (**book authors**), Introduction to Electromagnetic Inverse Problems in Radar Target/Clutter Scattering, John Wiley & Sons, Wave Propagation Series (J-A. Kong, Series Editor), Englewood Cliffs, N.J. 1989 (280 pages): in preparation, B.

I.7.2 Symposia/Conference/Workshop Planning, Organization, Execution and Chairmanships

During the past two decades I was invited with increasing frequency to participate in the planning, organization and execution of special sessions (S), main programs (several sessions: P) and/or entire Symposia, Conferences and Workshops (C) for

i) International Scientific/Technical Institutes

| | |
|-------------|--|
| IMPI | : 1969(S), 1970(S,P), 1971(s) |
| IEEE-APS | : 1977(S), 1978(S), 1979(S,P), 1980(S,P), 1981(S) 1982(S), 1983(S), 1984(S), 1985(S,P), 1986(S), 1988(S,P) |
| SPIE | : 1981(S) |
| IEEE-GSRS | : 1982(S), 1983(S), 1984(S) |
| OSA-Imaging | : 1983(S) |

- IEE (El-mag) : 1980(S), 1984(S), 1987(S)
 AIEE(Australia) : 1970(S), 1971(S)
 Jap-ISAS : ISAS-1(1970:S), ISAS-2(1978:S), ISAS-3(1985:S)
 Chinese IAEME : 1985(S), 1988(P,S,Co-C)
 URSI/USNC-B : 1980s(S), 1980W(S), 1981S(S), 1981W(S),
 1982S/W(S), 1983S/W(S), 1984W(S), 1985S(S),
 1986S(S)
 URSI/USNC-F : 1984(S), 1985(S), 1986(S)
 URSI/CAN-B : 1971(S), 1974(S)
 URSI/FRG-B : 1984(S), 1985(S)
 URSI/Gen. Assembly-B/F: 1981(S), 1984(S), 1987(S)
- ii) US Department of Defense Expert Workshops
 ONR : 1980(S), 1982(S), 1984(S), 1985(S), 1986(S)
 ONR-BR-OF-Tokyo : 1986(S)
 ONR-BR-OF-London: 1983(S), 1985(S), 1987(S)
 ARO : 1985(S), 1986(S)
 MI-LAB : 1981(S), 1984(S,P,Co-C), 1988(Co-C)
 AFOSR : 1981(S), 1983(S), 1987(S)
 NASA : 1980(S), 1982(S), 1983(S)
- iii) NATO
 NATO-AGARD : 1983(S), 1984(S), 1985(S), 1986(P,S), 1987(C,P,S)
 NATO-SHAPE : 1982(S), 1983(C,P,S)
 NATO-SAD : 1983(C,P,S), 1988(C,P,S)
- iv) National Industry
 (See Curriculum Vitae: Consulting/Short Courses/Workshops
 organized/executed by W-M. Boerner on Electromagnetic Inverse Problems
 and Radar Polarimetry)
- | | |
|--|----|
| Short Course Lecture Series (5 days): | 6 |
| Short Course Lecture Series (3 days): | 12 |
| Short Course Lecture Series (2 days): | 24 |
| Short Course Lecture Series (1 day): | 37 |
| Workshop Contributions (30 hrs. and more): | 3 |
| Workshop Contributions (20 hrs. and more): | 5 |
| Workshop Contributions (10 Hrs. and more): | 14 |
| Workshop Contributions (4 hrs. and more): | 18 |
| Workshop Contributions (1/2 lectures): | 23 |
- v) Learned Societies
 (Invited Keynote addresses on Polarimetry in nature (6);
 Geoelectromagnetic storm interaction with man-made systems in boreal
 auroral regions (12); Earth/sea-quake geo. electromagnetic precursor
 radiation phenomena (9) presented by W-M. Boerner)

I.7.3 Overview (1988 July 31)

Current (in progress), and reused (+)

Theses: 2
 Monographs: 4(2)
 Keynote Address: 30(6)
 Communications: 95(18)
 Wkshp Notes: 18+
 Patents: 6(4)
 Adm. Report: 6(2)+
 Newsletter: 36
 Lab. Manuals: 12(4)+

Books: 2(2)
 Invited Review: 40(6)
 Journal Paper: 87(28)
 Symp./Conf. Paper: 139(12)
 Gov. Reports: 45(6)
 Lab. Report: 73+
 Interaction Notes: 5/mo+
 Newspaper: 42(1)
 Proceedings: 4(2)

I.7.4 Books

W-M. Boerner et al., (eds.) Inverse Methods in Electromagnetic Imaging, Parts 1 & 2, NATO ASI Series C: Mathematical & Physical Sciences, Vol. 143, D. Reidel Publishing Co., Dordrecht/Boston/Lancaster, January 1985.

SOC-MOTH (NATO), Advanced Research Short Course, Vector Inverse Methods in Radar Target/Clutter Imaging, Co-Editor, (W.M. Boerner, F.A. Molinet, H. Uberall), Proceedings, ARSC, Ecole Supérieur d' Electricite, Gif-sur-Yvette, France, 1986, Sept. 1-4, Springer Verlag, Heidelberg, 1988, total pages: 428.

NATO, Advanced Research Workshop on Direct and Inverse Methods in Radar Polarimetry, Sept. 18-24, 1988, Proceedings, Chief Editor, 1987-1989, (1,500 pages), D. Reidel Publ. Co., Dordrecht, NC, exp. 1989/1990.

Chan, C-Y. and Boerner, W-M., (Invited Monograph), Inverse Methods in Electromagnetic Imaging, pp. 213-238. Medical Applications of Microwave Imaging, (eds. L.E. Larsen and J.H. Jacob), IEEE Press, New York, 1986.

I.7.5 Publications (Chronological Order)

Refereed Journals

B-Y. Foo, S.K. Chaudhuri, and W-M. Boerner, "A High Frequency Inverse Scattering Model to Recover the Specular Point Curvature from Polarimetric Scattering Matrix Data," IEEE Transactions on Antennas & Propagation, vol. AP-32 (11) pp. 1174-1178, November 1984.

S.K. Chaudhuri and W-M. Boerner, "A Polarimetric Model for the Recovery of the High-Frequency Scattering Centers From Bistatic-Monostatic Scattering Matrix Data," submitted for publication in the IEEE Transactions on Antennas & Propagation, Vol. 35, No. 1, pp. 87-93, Jan. 1987.

A.B. Kostinski and W-M. Boerner, "On Foundations of Radar Polarimetry," accepted for publication in the IEEE Transactions on Antennas & Propagation, Vol. AP-34, No. 12, pp. 1395-1404, also see: comments by H. Mieras, pp. 1470-1471, and Author's Reply, pp. 1471-1473, Dec. 1986.

S.K. Chaudhuri, B-Y. Foo and W-M. Boerner, "A Validation Analysis of Huynen's Target-Descriptor Interpretations of the Mueller Matrix Elements in Polarimetric Radar Returns Using Kennaugh's Physical Optics Impulse Response Formulation," IEEE Transactions on Antennas & Propagation, vol. AP-34, no. 1, pp. 11-20, January 1986.

W-M. Boerner, B.-Y. Foo, H.J. Eom, "Interpretation of the Polarimetric Co-Polarization Phase Term ($\phi_{HH} - \phi_{VV}$) in High Resolution SAR Imaging Using the JPL CV-990 Polarimetric L-Band SAR Data," submitted for

publication in the Special IGARSS'85 Issue of the IEEE Transactions on Geoscience & Remote Sensing, Vol. GE-25, No. 1, pp. 77-82, Jan. 1987.

- H.J. Eom and W-M. Boerner, "A Re-examination of Radar Terrain Backscattering at Nadir," IEEE Transactions on Geoscience & Remote Sensing, vol. GE-24, No. 2, pp. 232-237, March 1986.
- M. Davidovitz and W-M. Boerner, "Extension of Kennaugh's Optimal Polarization Concept to the Asymmetric Scattering Matrix Case," accepted for publication in the IEEE Transactions on Antennas & Propagation, Vol. AP-34, No. 4, pp. 569-574, April 1986.
- H.J. Eom and W-M. Boerner, "Scattering from a Layered Medium Connected With Rough Interfaces: Matrix Doubling Method," IEEE Trans. Geoscience & Remote Sensing, Vol. GE-24, No. 6, pp. 937-939, Nov. 1986.
- W-M. Boerner (INVITED), "Inverse Methods in Electromagnetic Scattering," (translated to Chinese by Prof. S.M. Lin) China, IEEE Trans. A & P Journal, (subm. June 1986, acc. May 1987), May 1988.
- A.P. Agrawal and W-M. Boerner, "Re-Development of Kennaugh's Characteristic Polarization Theory Using the Polarization Transformation Ratio Formalism for the Coherent Case," IEEE Trans. on Geoscience Electronics, (subm. Oct. 1986, acc. Nov. 1987), October 1988.
- Lin, S.M. and W-M. Boerner, "On the Discrete Radon Transform," J.N.W. Polytechnical Univ., Vol. 6, No. 2, pp. 173-180, April 1988.
- B-Y. Foo, S.K. Chaudhuri, and W-M. Boerner, "Extension of Kennaugh-Cosgriff's Formula to the Bistatic Case and Applications to Electromagnetic Direct and Inverse Scattering," IEEE Trans. A&P, (subm. October 1986, acc. May 1987), Sept. 1988.
- A.P. Agrawal and W-M. Boerner, "Description of Polarimetric Backscatter Radar Model for Distributed Scatterers for the Partially Polarized Case," Radio Science, (subm. October 1986, acc. Aug. 1987), Nov. 1988.
- A.B. Kostinski, B.D. James, and W-M. Boerner, "On the Optimal Reception of Partially Polarized Waves," J. Optical Society of America, Part A, Optics & Image Sciences, Series 2, Vol. 5(1), pp. 58-64, Jan 1, 1988.
- A.B. Kostinski and W-M. Boerner, "On the Polarimetric Contrast Optimization," IEEE Trans. A&P, Vol 35(8), pp. 988-991, Aug. 1987.
- W-M. Boerner, "Recent Advances in Polarization Radar & Polarimetric Radiometer Technology - An Introduction of Basic Concepts and an Overview of the Historical Development with Applications and Projections of Future Trends," IEEE Aerospace & Electronics Systems Society Journal, to appear March 1988.
- A.P. Agrawal, D.W. Carnegie and W-M. Boerner, "Evaluation of Dual Polarization Scattering Matrix Radar Rain Scatter Measurements in the X- and Q-bands," Radio Sciences, (subm. Nov. 1986, acc. May 1987), Aug. 1988.
- W-M. Boerner and A.B. Kostinski, "On the Historical Development of Radar Polarimetry - A Critical Assessment of the State-of-the-Art," in Progress in Optics, submitted Dec. 1986, (in review).

- W-M. Boerner, A.B. Kostinski and M. Tanaka, "The Design of the Polarization Matched Filter and Its Application in High Resolution Polarimetric (Scattering Matrix) Imaging," IEEE Trans. Ant. & Prop., (subm. May 1987, acc. Jan 1988), in review.
- R.M. Lempkowski, A.B. Kostinski, and W-M. Boerner, "Calibration Requirements for Polarimetric Scattering Matrix Radar," IEEE Trans. Ant. & Prop., (subm. May 1987, acc. Nov. 1987) (in progress).
- B.D. James and W-M. Boerner, "An Examination of some Theoretical and Computational Aspects of Diffraction Tomography," Inverse Problems, submitted Dec. 1987 (in progress).
- B.D. James and W-M. Boerner, "The Effects of Data and Computational Errors in Diffraction Tomography," J. Optical Soc. Amer., Submitted Dec. 1986.
- B.D. James and W-M. Boerner, "Canonical Examples of Diffraction Tomography - Reconstruction of a Sphere and an Aperture," IEEE Ant. & Prop., submitted Dec. 1986.
- A.B. Kostinski, B.D. James and W-M. Boerner, "Polarimetric Matched Filter for Coherent Imaging," Canadian Journal of Physics, Special Issue on Optics and Modern Image Processing, (subm. Jan 1988, acc. April 1988, to appear Dec. 1988).
- A.B. Kostinski, B.D. James and W-M. Boerner, "The Polarimetric Matched Image Filter and its Application to POL-Sar Image Analysis," IEEE Trans. AES, (subm. March 1988, acc. May 1988, to appear Nov. 1988).
- W-M. Boerner, A.B. Kostinski, B.D. James and M. Walther, "Statistical Analysis of SAR Images and Terrain Classification, Part 1: Rough Surface Scattering," IEEE Trans. on Geoscience & Remote Sensing. (subm. Nov. 1987).
- A.B. Kostinski and W-M. Boerner, "Study of the Equivalence of the Mueller and Jones Methods From the Measurement Time Point of View," J. Opt. Soc., (subm. Dec. 1987).
- A.B. Kostinski, J. Okeke and W-M. Boerner, "On the Physical Realizability of Mueller Matrices Under the Consideration of Various Inequalities," Inverse Problems, in preparation, Dec. 1987
- Boerner, W-M., "Electromagnetic Inverse Methods - A State of the Art Review," (Invited); IEEE/APS-Section Tokyo, IECE of Japan, Sect. A&P, Vol. 86-20, pp. 71-77, May 1986
- B.D. James and W-M. Boerner, "An Examination of Some Theoretical and Computational Aspects of Diffraction Tomography Inverse Problems (International Institute of Physics, Bristol, UK), (subm. Dec. 1987).
- B.D. James and W-M. Boerner, "The Effects of Data and Computational Errors in Vector Diffraction Tomography," J. Opt. Soc. Am., Fall 1987.
- S.K. Chaudhuri and W-M. Boerner, "A Polarimetric Model for the Suppression of Multipath Ghost Images in Dual Polarization Real and Synthetic Aperture Radar Target Mapping Using Monostatic and Bistatic Scattering Matrix Data," IEEE Trans. A&P, (subm. June 1987).

- A.B. Kostinski, J.O. Okeke and W-M. Boerner, "On the Physical Realizability of Mueller Matrices in View of the Over-Polarization Inequalities," Inverse Problems, in preparation.
- A.B. Kostinski, B.D. James, M. Walther and W-M. Boerner, "Generation of Mueller Matrices in the Long Exposure Limit by Construction of Jones Matrix Time Series," Appl. Optics, in preparation.
- A.B. Kostinski, M. Walther and W-M. Boerner, "Polarimetric Matched Signal Filter Design from a Communication Point of View," IEEE Trans. Comm., in preparation.
- A.B. Kostinski, J. Okeke and W-M. Boerner, "On the Physical Realization of Mueller Matrices," Appl. Optics, in preparation.
- A.B. Kostinski, M. Walther and W-M. Boerner, "Polarimetric Matched Image Filter Design (II) for SAR Image Interpretation," IEEE Trans. Geosci. and Remote Sensing, in preparation.
- W-M. Boerner and A.B. Kostinski, "On the Historical Development of Radar Polarimetry - A Critical Assessment of the State-of-the-Art," Progress in Optics, in preparation.
- R.M. Lempkowski and W-M. Boerner, "Calibration Requirements for Polarimetric Scattering Matrix Radar," IEEE Trans. Ant. & Prop., (subm. Spring 1988).

Conference Papers

- A.K. Jordan and W-M. Boerner, "Inverse Methods in Electromagnetic Imaging: Overview," Proceedings of the NATO-ARW-1983 on Inverse Methods in Electromagnetic Imaging, NATO-ASI Series C: Mathematical & Physical Sciences, vol. 143, Part 1, pp. 32-41, published by D. Reidel Publishing Co., Dordrecht/Lancaster/Boston, January 1985.
- M. Davidovitz and W-M. Boerner, "Extension of Kenraugh's Optimal Polarization Concept to the Asymmetric Matrix Case," Proceedings of the NATO-ARW-1983 on Inverse Methods in Electromagnetic Imaging, NATO-ASI Series C: Mathematical & Physical Sciences, vol. 143, Part 1, pp. 598-617, published by D. Reidel Publishing Co., Dordrecht/Lancaster/Boston, January 1985.
- J.D. Nespor, A.P. Agrawal and W-M. Boerner, "Theory and Design of a Dual Polarization Radar for Clutter Analysis," Proceedings of the NATO-ARW-1983 on Inverse Methods in Electromagnetic Imaging, NATO-ASI Series C: Mathematical & Physical Sciences, vol. 143, Part 1, pp. 631-655, published by D. Reidel Publ. Co., Dordrecht/Lancaster/Boston, January 1985.
- A.C. Manson and W-M. Boerner, "Interpretation of High Resolution Polarimetric Radar Target Downrange Signatures," Proceedings of the NATO-ARW-1983 on Inverse Methods in Electromagnetic Imaging, NATO-ASI Series C: Mathematical & Physical Sciences, Vol. 143, Part 2, pp. 689-718, January 1985.
- C-Y. Yang and W-M. Boerner, "Extension of Scalar to Vector Propagation Tomography," Proceedings of the NATO-ARW-1983 on Inverse Methods in Electromagnetic Imaging, NATO-ASI Series C: Mathematical & Physical

Sciences, vol. 143, Part 2, pp. 1142-1147, published by D. Reidel Publ. Co., Dordrecht/Lancaster/Boston, January 1985.

- H.J. Eom and W-M. Boerner, "A Re-Examination of Radar Terrain Backscattering at Nadir," Proceedings of the 1985 National Radar Conference, Washington, D.C. pp. 232-234, May 7-10, 1985.
- A.P. Agrawal, H.J. Eom and W-M. Boerner, "Use of Dual Polarization Radar for Polarimetric Clutter Suppression," 1985 North American Radio Science Meeting & Int'l. IEEE/AP-S Symposium, Vancouver, Canada, Symposium Digest, Vol. II, IEEE Catalog No. 85CH2128-7, pp. 741-744, June 17-21, 1985.
- S.K. Chaudhuri and W-M. Boerner, "Polarimetric Recovery of High Frequency Scattering Centers from Bistatic-Monostatic Scattering Matrix Data," 1985 North American Radio Science Meeting & Int'l. IEEE/AP-S Symposium, Vancouver, Canada, Symposium Digest, Vol. II, IEEE Catalog No. 85CH2128-7, pp. 737-740, June 17-21, 1985.
- H.J. Eom, A.M. Khounsary and W-M. Boerner, "A Theory of Scattering from an Inhomogeneous Multi-Layer Connected with Irregular Interfaces," Proceedings of the 1985 International Symposium on Antennas & Propagation (ISAP'85), Beijing, China, pp. 834-838, August 26-28, 1985.
- S.K. Chaudhuri, B-Y. Foo and W-M. Boerner, "Use of Bistatic/Monostatic Scattering Matrix Data for the Polarimetric Recovery of High Frequency Target Scattering Centers," Proceedings of the 1985 International Symposium on Antennas & Propagation (ISAP'85), Beijing, China, pp. 839-842, August 26-28, 1985.
- S.K. Chaudhuri and W-M. Boerner, "A Polarimetric Model of High frequency Scattering Centers and its Application in Microwave Multipath Imaging Analyses," Proceedings of the International Symposium on Antennas & Propagation (ISAP'85), Kyoto, Japan, vol. II, pp. 703-706, August 20-22, 1985.
- H.J. Eom, A.P. Agrawal and W-M. Boerner, "Optimum Polarization Concept for Polarimetric Clutter Suppression," Proceedings of the International Symposium on Antennas & Propagation (ISAP'85), Kyoto, Japan, vol. II, pp. 707-710, August 20-22, 1985.
- S.K. Chaudhuri and W-M. Boerner, "Multi-(Bi)-Static High Frequency (PO/GO) Radar Target Imaging of Airborne Scatterers," NATO-AGARD Conference Preprint No. 381, Multifunction Radar for Airborne Applications, pp. 27-1 thru 27-11, Avionics Panel Symposium, Toulouse, France, Oct. 14-18, 1985.
- B-Y. Foo, S.K. Chaudhuri and W-M. Boerner, "Basic Monostatic Polarimetric Broadband Target Scattering Analysis Required for High Resolution Polarimetric Radar Target Downrange/Crossrange Imaging of Airborne Scatterers," NATO-AGARD Conference Preprint No.381, Multifunction Radar for Airborne Applications, pp. 26-1 thru 26-9, Avionics Panel Symposium, Toulouse, France, Oct. 14-18, 1985.
- A.P. Agrawal, H.J. Eom and W-M. Boerner, "An Analysis of Polarimetric (VV, HH, & VH Polarized) Scattering Matrix Data of Near-Grazing Sea Backscatter at X-Band," to appear in Proceedings of the 4th Working Symposium on Oceanographic Data Systems, Scripps Institution of

Oceanography, LaJolla, CA, 11 pp. Feb. 4-6, 1986.

- W-M. Boerner, "Recent Advances in Radar Polarimetric Metrology and Vector Signal Processing vs. Azimuth for Multi-(Mono/Bi)- Static Measurement Set-Ups," Research Paper Presentation at the RAT-SCAT Facilities, 6585th Test Group/RX, Holloman AFB, N.M., January 13, 1986.
- A.P. Agrawal and W-M. Boerner, "Polarimetric Backscatter Model for Hydrometeors (Raindrops) Based on Kennaugh's Null Polarization Theory," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- D.W. Carnegie, A.P. Agrawal and W-M. Boerner, "Experimental Determination of the Scattering Matrix for Rain in the X- and Q-Bands," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- H.J. Eom, J. Okeke and W-M. Boerner, "A Simple Radar Backscatter Model for Near Grazing Sea," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- B-Y. Foo and W-M. Boerner, "Interpretation of Kennaugh's Physical Optics Impulse Response Approach for the Slightly Bistatic Case," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- B-Y. Foo, W-M. Boerner and S.K. Chaudhuri, "A High Frequency Inverse Scattering Model for Smooth, Convex, Conducting Scatterers in the Slightly Bistatic Case," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- B.D. James and W-M. Boerner, "Vector Diffraction Tomography in Computer-Assisted Electromagnetic Imaging," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- A.M. Khounsary and W-M. Boerner, "General Reciprocity and Symmetry Relationships for the Polarized Radiative Field in Plane-Parallel Media," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- A.B. Kostinski and W-M. Boerner, "Polarimetric Radar Signal Optimization in the Partially Polarized Case for Target Detection in Clutter," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- A.B. Kostinski and W-M. Boerner, "Extension of Kennaugh's Polarimetric Radar Signal Optimization Problem to the Non-Reciprocal Bistatic Case," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- S-M. Lin and W-M. Boerner, "On a New Generalization of Taylor Pattern for the Circular Aperture Antenna," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- M. Walther and W-M. Boerner, "Assessment of Polarimetric Millimeter Wave Sensors in the Design of Airborne/Marine Ground Vehicle Collision Avoidance and Traffic Flow Control Radars," presented at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.

- W-M. Boerner, B-Y. Foo and H.J. Eom, "Further Advancements in Interpretation of the Polarimetric Co-Polarization Phase Term ($\phi_{HH}-\phi_{VV}$) in High Resolution SAR Imaging," presented at the URSI-F Wave Propagation & Remote Sensing Symposium, University of New Hampshire, Durham, July 28 to August 1, 1986.
- W-M. Boerner and A.B. Kostinski (INVITED), "Inverse Problems of Radar Polarimetry," RCP-264: Problemes Inverses, USTL, Montpellier, France, Dec. 1-4, 1986 (paper presented during Editors' Meeting, Techno House, Bristol, U.K., Sept. 24, 1986).
- W-M. Boerner, B-Y. Foo, and H.J. Eom, "Further Advancement in the Interpretation of the Polarimetric Co-Polarization Phase-Term in High Resolution SAR Imaging," International URSI Conference, Wave Propagation & Remote Sensing Symposium, Univ. of New Hampshire, Durham, July 28 - Aug. 1, 1987.
- W-M. Boerner, (INVITED) "Recent Advances in Radar Polarimetry - Current State-of-the-Art," Fifth Int. Conf. on Antenna and Prop., ICAP 1987, Univ. of York, UK, March 30 - April 2, 1987, Proceedings, Part II, pp. 2.359 - 2.363.
- W-M. Boerner, (INVITED), "The Electromagnetic Inverse Problem - Current State-of-the-Art," Fifth Int. Conf. on Antenna and Prop., ICAP 1987, Univ. of York, UK, March 30 - April 2, 1987, Proceedings, Part I, pp. 1.462 - 1.466.
- A.P. Agrawal, D.W. Carnegie, and W-M. Boerner, "Evaluation of Dual Polarization Scattering Matrix Radar Rain Scatter Measurements in the X- and Q-band," Fifth Conf. on Antennas & Propagation, ICAP 1987, University of York, UK, March 30 - April 2, 1987, Proceedings, Part II, pp. 2.243 - 2.247.
- H.J. Eom and W-M. Boerner, "Re-Examination of Phase Difference Observed in SAR Imaging of Corn Canopy," IGARSS '87, Remote Sensing of the Terrestrial Underground and the Earth as a System, Ann Arbor, MI, May 18-21, 1987.
- W-M. Boerner, (INVITED KEY-NOTE Speaker), "Basic Principles of Radar Polarimetry and its Applications to Target Recognition Problems," NATO Advanced Study Institute, Electromagnetic Theory and Measurements for Analysis and Synthesis Problems, Pascoli, Tuscany, Italy, August 10-21, 1987.
- B.D. James and W-M. Boerner, (INVITED) "Vector Diffraction Tomography Paraphraphy Using Radar Transform Techniques in Computer-Assisted Electromagnetic Remote Sensing," XXII General Assembly of URSI, Tel Aviv, Israel, Open Symposium on Reconstruction, Imaging and Inverse Scattering, August 26, 1987.
- B-Y Foo and W-M Boerner, "Polarization Correction and Extension of Kennaugh-Cosgriff's Target-Ramp Response to the Bistatic Case," XXII General Assembly of URSI, Tel Aviv, Israel, Open Symposium on Reconstruction, Imaging and Inverse Scattering, August 26, 1987.
- A.B. Kostinski and W-M Boerner, "Optimal Reception of Partially Polarized Waves," XXII General Assembly of URSI, Tel Aviv Israel, Open Symposium on Reconstruction, Imaging and Inverse Scattering, August 26, 1987.

- A.B. Kostinski and W-M Boerner, "Formulation of Proper Standards in Radar Polarimetry," Special Session on Measurement Standards: opening paper, Ninth Annual Meeting and Symposium of the Antenna Measurement Techniques Association, Seattle, WA, September 28, 1987.
- A.B. Kostinski and W-M. Boerner, (INVITED), "Formulation of Proper Standards in Radar Polarimetry," ISRP-88, Section 7, Paper No. 1, International Symposium on Radio Propagation, Fragrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.
- B.D. James and W-M. Boerner, "Toward Increased Image Fidelity in Microwave Diffraction Tomography," ISRP-88, Section 7, Paper No. 2, International Symposium on Radio Propagation, Fragrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.
- B-Y. Foo and W-M. Boerner, "On the Bistatic Formulation of the Physical Optics Inverse Scattering Problem in Radar Polarimetry and Imaging," ISRP-88, Section 7, Paper No. 5, International Symposium on Radio Propagation, Fragrant Hill hotel, Beijing, P.R. China, 1988, April 18-21.
- A.B. Kostinski, B.D. James and W-M. Boerner, "On the Optimal Reception of Partially Polarized Waves," ISRP-88, Section 7, Paper No. 6, International Symposium on Radio Propagation, Fragrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.
- A.P. Agrawal and W-M. Boerner, "On the Concept of Optimal Polarization in Problems of Radio Wave Propagation and Probing," ISRP-88, Section 7, Paper No. 8, International Symposium on Radio Propagation, Gagrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.
- B. Foo and W-M. Boerner, "On The Bistatic Formulation of The Physical Optics Inverse Scattering Problem in Radar Polarimetry and Imaging," IEEE-APS/URSI International Symposium 1988, URSI-B, Section 6, Paper 6, Syracuse, N.Y. 1988 June 6-10.
- H.J. Eom and W-M. Boerner, "Rough Surface Incoherent Backscattering of Spherical Wave," IEEE-APS/URSI Int. Symposium 1988, URSI-F, Section 17, Paper 1, Syracuse, N.Y. 1988 June 6-10.
- H.J. Eom and K.Y. Kim, "A Slightly Random Rough Surface-How Good Conserve Energy?", IEEE-APS/URSI Int. Symposium 1988, URSI-F, Section 17, Paper 2, Syracuse, N.Y. 1988 June 6-10.
- W-M. Boerner and A.B. Kostinski, "Formulation of The Proper Equations for Developing Standards in Radar Polarimetry," IEEE-APS/URSI Int. Symposium 1988, AP-S, Section 30, Paper 1, Syracuse, N.Y. 1988 June 6-10.
- W-M. Boerner and A.B. Kostinski, "On The Concept of The Polarimetric Matched Filter in High Resolution Radar Imaging," IEEE-APS/URSI Int. Symposium 1988, AP-S, Section 30, Paper 4, Syracuse, N.Y. 1988 June 6-10.
- A.B. Kostinski, B.D. James and W-M. Boerner, "On The Optimal Reception of Partially Polarized Waves," IEEE-APS/URSI Int. Symposium 1988, AP-S, Section 30, Paper 7, Syracuse, N.Y. 1988 June 6-10.
- B.D. James and W-M. Boerner, "Towards Increased Image Fidelity in Microwave

- Diffraction Tomography," IEEE-APS/URSI Int. Symposium 1988, AP-S, Section 43, Paper 2, Syracuse, N.Y. 1988 June 6-10.
- A.B. Kostinski, B.D. James and W-M. Boerner, "Polarimetric Matched Image Filter for Pol-Sar Image Interpretation of Ocean Surface Scatter," IEEE-aps/URSI Int. Symposium 1988, URSI-F, Section 68, Paper 1, Syracuse, N.Y. 1988 June 6-10.
- M. Walther, A.B. Kostinski, H.J. Eom and W-M. Boerner, "Statistical Analysis and Some Polarimetric Signatures of Pol-Sar Images," IEEE-APS/URSI Int. Symposium 1988, URSI-F, Section 68, Paper 2, Syracuse, N.Y. 1988 June 6-10.
- J. Okeke, A.B. Kostinski, H.J. Eom and W-M. Boerner, "Generation of a 4x4 Mueller Matrix From a 2x2 Scattering Matrix Time Series," IEEE-APS/URSI Int. Symposium 1988, URSI-F, Section 68, Paper 5, Syracuse, N.Y. 1988 June 6-10.
- A.P. Agrawal and W-M. Boerner, "On The Concept of Optimal Polarizations in Problems of Radio Wave Propagation," IEEE-APS/URSI Int. Symposium 1988, Joint AP-S, URSI-E, Section 71, Paper 6, Syracuse, N.Y. 1988 June 6-10.
- B.D. James, A.B. Kostinski and W-M. Boerner, "Optimal Reception in Depolarizing Rain Clutter," IEEE-APS/URSI Int. Symposium 1988, URSI-F, Section 80, Paper 1, Syracuse, N.Y. 1988 June 6-10.
- R.B. Lempkowski, S.K. Chadhuri, A.B. Kostinski and W-M. Boerner, "Measurement Procedures for Target Scattering Matrices in Both Monostatic and Bistatic Arrangements for The Coherent and Partially Coherent Cases," IEEE-APS/URSI Int. Symposium 1988, Joint AP-S, URSI-A, Section 81, Paper 4, Syracuse, N.Y. 1988 June 6-10.
- H.J. Eom, M. Walther and W-M. Boerner, "Statistical Properties of Phase Differences between Two Orthogonally Polarized SAR Signals," IGARSS'88, Section/Paper, TUP3-3, Edinburgh, Scotland, U.K., 1988 Sept. 12-16.
- B.D. James, A.B. Kostinski and W-M. Boerner, "Optimal Reception in Depolarization Clutter," IGARSS'88, Section 2, Paper 1, WEA2-1, Edinburgh, Scotland, U.K., 1988 Sept. 12-16
- W-M. Boerner and A.B. Kostinski, "On the Concept of the Polarimetric Matched Filter in High Resolution Radar Imaging: An Alternative for Speckle Reduction," Section 3, Paper 5, TUP3-5, Edinburgh, Scotland, U.K., 1988 Sept. 12-16.
- B.D. James, A.B. Kostinski and W-M. Boerner, "Polarimetric Matched Image Filter for POL-SAR Image Interpretation of Ocean Surface Scatter," Section 3, Paper 4, TUP3-4, Edinburgh, Scotland, U.K., 1988 Sept. 12-16.
- W-M. Boerner, H.J. Eom and A.B. Kostinski, "Formulation of the Proper Equation for Developing Standards in Coherent Dual Polarization SAR Imaging," Section 3, Paper 8, WEA3-8, Edinburgh, Scotland, U.K., 1988 Sept. 12-16.
- W-M. Boerner, H.J. Eom and A.B. Kostinski, "POL-SAR Calibration Requirements for the Proper Implementation of the Polarimetric Matched Filter (PMIF) Technique in High Resolution Polarization SAR Imaging," Section 3,

Paper 9, WEA3-9, Edinburgh, Scotland, U.K., 1988 Sept. 12-16.

- M. Walther, A.B. Kostinski, H.J. Eom and W-M. Boerner, "Statistical Analyses and Some Polarimetric Signatures of POL-SAR Images," Section 3, Paper 2, TUP3-2, Edinburgh, Scotland, U.K., 1988 Sept. 12-16.
- H.J. Eom, A.B. Kostinski and W-M. Boerner, "On the Proper Formulation of Calibration Standards in Radar Polarimetry and POL-SAR Imaging," Third Polarimetric Technology Workshop, Session 2, Paper 4, Redstone Arsenal, AL, Aug. 16-18, 1988.
- A.B. Kostinski and W-M. Boerner, "On the Foundations of Radar Polarimetry," Third Polarimetric Technology Workshop, Session 4, Paper 1, Redstone Arsenal, AL, Aug. 16-18, 1988.
- A.B. Kostinski, B.D. James, W-M. Boerner, "On the Optimal Reception of Partially Polarized Waves," Third Polarimetric Technology Workshop, Session 4, Paper 3, Redstone Arsenal, AL, Aug. 16-18, 1988.
- A.B. Kostinski, B.D. James and W-M. Boerner, "Fundamental Description of the Polarimetric Matched Image Filter Technique for Contrast Optimization of Target Versus Clutter in POL-SAR Imaging," Third Polarimetric Technology Workshop, Session 5, Paper 3, Redstone Arsenal, AL, Aug. 16-18, 1988.
- B.D. James, A.B. Kostinski, W-M. Boerner, "Application of the Polarimetric Image Filter (PMIF) Technique to Clutter Reduction of POL-SAR Images of the Ocean, Flora and Urban Environment," Third Polarimetric Technology Workshop, Session 5, Paper 5, Redstone Arsenal, AL, Aug. 16-18, 1988.
- A.F. Agrawal and W-M. Boerner, "On the Concept of Optimal Polarizations in Radar Meteorology," Third Polarimetric Technology Workshop, Session 6, Paper 1, Redstone Arsenal, AL, Aug. 16-18, 1988.
- B.D. James, J.D. Nespor, A.B. Kostinski, W-M. Boerner, "Evaluation of Polarimetric Rain Backscatter Data Using the Concept of Optimal Reception of Partially Polarized Waves," Third Polarimetric Technology Workshop, Session 6, Paper 3, Redstone Arsenal, AL, Aug. 16-18, 1988.
- B.D. James, A.B. Kostinski, W-M. Boerner, "The Polarimetric Matched Image Filter in POL-SAR Image Interpretation, Modeling, and Analysis," Third Polarimetric Technology Workshop, Session 7, Paper 4, Redstone Arsenal, AL, Aug. 16-18, 1988.
- W-M. Boerner, "Historical Development of Radar Polarimetry - Unresolved Problems - Incentives for this Workshop," NATO-ARW-DIMRP '88, Session 0, Paper 1, Bad Windsheim, FRG, Sept. 18-24, 1988.
- A.B. Kostinski, W-M. Boerner, "Fundamental Equations of Radar Polarimetry," NATO-ARW-DIMRP '88, Session 1, Paper 3, Bad Windsheim, FRG, Sept. 18-24, 1988.
- A.B. Kostinski, B.D. James, W-M. Boerner, "Optimal Reception of Partially Polarized Waves," NATO-ARW-DIMRP '88, Session 2, Paper 2, Bad Windsheim, FRG, Sept. 18-24, 1988.
- B-Y. Foo, S.K. Chaudhuri, W-M. Boerner, "Specular Target Geometry and Scattering Matrices," NATO-ARW-DIMRP '88, Session 3, Paper 3, Bad

Windsheim, FRG, Sept. 18-24, 1988.

N. Soliman, B.D. James, A.B. Kostinski, W-M. Boerner, "The Depolarizing Term in Electromagnetic Vector Diffraction Tomography," NATO-ARW-DIMRP '88, Session 7, Paper 4, Bad Windsheim, FRG, Sept. 18-24, 1988.

B.D. James, A.B. Kostinski, W-M. Boerner, "The Polarimetric Matched Image Filter and its Application to POL-SAR Imaging," NATO-ARW-DIMRP '88, Session 11, Paper 3, Bad Windsheim, FRG, Sept. 18-24, 1988.

Company or Departmental Reports

- W-M. Boerner, et al., "Polarimetric Recovery of the High-Frequency Scattering Centers from Bistatic-Monostatic Scattering Matrix Data," Final Research Report for Westinghouse Electric Corp., Order No. 86EJ-HA-30690 OV, November 15, 1984.
- W-M. Boerner, et al., "Interpretation of High Resolution Polarimetric Radar Downrange Signatures," Final Report No. UIC-EECS-EMID-83-09-30 for U.S. Naval Sea Contract No. N62296-83-R-0317, November 15, 1984.
- W-M. Boerner, et al., "Development of Polarimetric Target Characteristic Classification Algorithms Applied to Armored Vehicles," Initiation Report No. UIC-EECS-CL-84-11-30 for U.S. Army ERADCOM Contract No. USA-ERADCOM/DELCS-4-84-19598, November 30, 1984.
- W-M. Boerner, et al., "Polarimetric Treatments of Microwave Multipath Target Imaging Analyses," Final Research Report for General Dynamics Purchase Order No. 614972, December 10, 1984.
- W-M. Boerner, A.B. Kostinski, et al., "Stationary Target Detection/-Classification Algorithm Development Applied to Armored Vehicle Detection in Ground/Tropospheric Clutter," UIC-EECS/Communications Laboratory Final Report #ARO/HDL-85-10-14 for U.S. Army Research Office & U.S. Army Laboratory Command, Contract No. DAAK21-84-C-0101, October 14, 1985.
- W-M. Boerner et al., "Analysis of High Resolution Polarimetric Radar Downrange Signatures Using RCS Matrix Measurement Data Based on Kennaugh's Target Characteristic Operator and Huynen's Mueller Matrix Decomposition Theories," Semi-annual Progress Report for NADC Contract No. N62269-85-C-0383, January 13, 1986.
- W-M. Boerner and H.J. Eom, "Advancement of High Resolution Radar Polarimetry in Target vs. Clutter Detection, Discrimination, and Classification: A Basic Theory and Modeling of Polarimetric Clutter Phenomenology," UIC-EECS/Communications Laboratory Semi-Annual Progress Report for ARO Contract #DAAG29-85-K-0065, January 31, 1986.
- W-M. Boerner and A.P. Agrawal, "Monostatic Polarimetric Radar Backscatter Model for Rain," Contract No. DAAG29-81-D-0100, Delivery No. 1597 MI-COM, AMSMI-RD-AS-RF, Polarimetric Radar Section, Redstone Arsenal, AL, 35898-5253, Final Report, January 31, 1986.
- W-M. Boerner et al., "Advancement of Basic Radar Target Phenomenology for the General Bistatic and/or Anisotropic Monostatic Scattering Case," Semi-annual Progress Report for ONR/EL Contract No. N00014-80-C-0773, January 31, 1986.

- W-M. Boerner et al., "Basic Polarimetric Broadband/Multifrequency Signature Analysis Required for Electromagnetic Inverse Scattering Problems in Radar Target Imaging," Semi-annual Progress Report for ONR/NWC Contract No. N00014-85-K-0483, February 15, 1986.
- W-M. Boerner, Final Travel Report on JSPS/CAST Fellowships for collaboration with Universities of Tsucuba/Toyohashi/Chofu-Shi, Tokyo, Japan and Xi'an, Shaanxi, Province, P.R. China, 1987 August 15.
- W-M. Boerner, A.B. Kostinski, B.D. James, M. Walther, D.W. Carnegie, A.P. Agrawal, B-Y. Foo, S.K. Chaudhuri, X-Q. Huang, N. Soliman, "Graphical Depiction of Targets Using Polarized Radar Data: Analysis of High Resolution Polarimetric Radar Downrange Signatures Using RCS Matrix Measurement Data Based on Kenneough's Target Characteristic Operator and Huynen's Mueller Decomposition Theories," Final Report UIC-EECS/CL 1987-06-15, NADC, Contract No. N62269-85-C-0383, 1987 Sept. 11 (508 pages).
- W-M. Boerner, Final Travel Report on Sabbatical Research Year of Leave (Jan.-July 1987) from the University of Illinois at Chicago to the German Aerospace Research & Test Establishment: DFVLR-Oberpfaffenhofen, FRG and the Royal Norwegian Council of Science & Technology, Environmental Research Establishment: NTNF-PFM, Kjeller, Norway, 1987 Dec. 15.

Papers Presented, Seminar Talks Given & Other International & National Activities

- W-M. Boerner and A.B. Kostinski, "A Critical Review of Polarimetric Radar Theory," presented at the DARPA/TTO, Millimeter-Wave Tactical Sensors Program, MIT, Lincoln Laboratory, Lexington, MA., May 8-9, 1985 and at the NATO-RSG8 Delegates Meeting, DFVLR-OPH, FR Germany, May 21-23, 1985.
- W-M. Boerner, (Invited) Keynote, "Overview of the State-of-the-Art of Electromagnetic Inverse Scattering with Emphasis on Needed Mathematical Research," Univ. Delaware Workshop on "Inverse Methods in Electromagnetic Scattering," sponsored by the NASC, June 11-12, 1985.
- A. P. Agrawal and W-M. Boerner, "Basic Concepts for the Design of a Dual Polarization Radar for Clutter Analysis," presented at the Symposium on Multiple Scattering of Waves in Random Media & Random Rough Surfaces, The Pennsylvania State University, July 29-August 2, 1985.
- B-Y. Foo, S.K. Chaudhuri and W-M. Boerner, "Basic Monostatic Polarimetric Broadband Target Scattering Analysis Required for High Resolution Polarimetric Target Downrange Imaging," vol. 2 of the Measurement, Processing and Analysis of Radar Target Signatures Workshop Proceedings, The Ohio State University, September 10-13, 1985.
- A.B. Kostinski and W-M. Boerner, "On Foundations of Radar Polarimetry," Volume 2 of the Measurement, Processing and Analysis of Radar Target Signatures Workshop Proceedings, The Ohio State University, September 10-15, 1985.
- W-M. Boerner, B.-Y. Foo, H.J. Eom, "Interpretation of the Polarimetric Co-Polarization Phase Term ($\phi_{HH} - \phi_{VV}$) in High Resolution SAR Imaging

Using the JPL CV-990 Polarimetric L-Band SAR Data," presented at the IGARSS'85 Conference at Amherst Massachusetts, Oct. 7-9, 1985.

- W-M. Boerner and A.B. Kostinski, "A Critical Review of Polarimetric Radar Theory and its Application to High Resolution Polarimetric Radar Imaging," presented at the Annual Mtg. of URSI National Committee for the Federal Republic of Germany, Kleinheubach (Main), October 7-11, 1985.
- W-M. Boerner, "Recent Advances in Radar Polarimetric Metrology and Vector Signal Processing vs. Azimuth for Multi-(mono/bi)-static Measurement Set-ups," research paper presentation at the RAT-SCAT facilities, 6585th Test Group/RX, Holloman AFB, N.M., January 13, 1986.
- W-M. Boerner, "Advanced Radar Polarimetry and its Applications," New Course No. S2.19, given at the NATO-Carl-Cranz Gesellschaft e.V., Center Oberpfaffenhofen, FRG - West Germany, February 4-6, 1986.
- W-M. Boerner, "Recent Advances in Radar Polarimetry and its Immediate Importance to Airborne & Space Surveillance of the Ocean Environment," Invited lecture at the Office of Naval Research and the Naval Research Laboratory, Washington, D.C., March 25, 1986.
- A.P. Agrawal and W-M. Boerner, "Polarimetric Backscatter Model for Hydrometeors (raindrops) Based on Kennaugh's Null Polarization Theory," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- D.W. Carnegie, A.P. Agrawal and W-M. Boerner, "Experimental Determination of the Scattering Matrix for Rain in the X- and Q-Bands," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- H.J. Eom, J. Okeke and W-M. Boerner, "A Simple Radar Backscatter Model for Near Grazing Sea," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- B-Y. Foo and W-M. Boerner, "Interpretation of Kennaugh's Physical Optics Impulse Response Approach for the Slightly Bistatic Case," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- B-Y. Foo, W-M. Boerner and S.K. Chaudhuri, "A High Frequency Inverse Scattering Model for Smooth, Convex, Conducting Scatterers in the Slightly Bistatic Case," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- B.D. James and W-M. Boerner, "Vector Diffraction Tomography in Computer-Assisted Electromagnetic Imaging," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- A.M. Khounsary and W-M. Boerner, "General Reciprocity and Symmetry Relationships for the Polarized Radiative Field in Plane-Parallel Media," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- A.B. Kostinski and W-M. Boerner, "Polarimetric Radar Signal Optimization in

the Partially Polarized Case for Target Detection in Clutter," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.

- M. Walther and W-M. Boerner, "Assessment of Polarimetric Millimeter Wave Sensors in the Design of Airborne/Marine Ground Vehicle Collision Avoidance & Traffic Flow Control Radars," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- S-M. Lin and W-M. Boerner, "On a New Generalization of Taylor Pattern for the Circular Aperture Antenna," accepted (March 1986) for presentation at the 1986 IEEE AP-S & URSI Symposium, Philadelphia, PA., June 9-13, 1986.
- W-M. Boerner, B-Y. Foo, and H.J. Eom, "Further Advancement in the Interpretation of the Polarimetric Co-Polarization Phase-Term in High Resolution SAR Imaging," International URSI Conference, Wave Propagation & Remote Sensing Symposium, Univ. of New Hampshire, Durham, July 28 - Aug. 1, 1987.
- W-M. Boerner, (INVITED), "The Electromagnetic Inverse Problem - Current State-of-the-Art," Fifth Int. Conf. on Antenna and Prop., ICAP 1987, University of York, UK, 30 March-April 1987.
- A.P. Agrawal, D.W. Carnegie, and W-M. Boerner, "Evaluation of Dual Polarization Scattering Matrix Radar Rain Scatter Measurements in the X- and Q-band," Fifth Conf. on Antennas & Propagation, ICAP 1987, University of York, UK, March 30 - April 2, 1987.
- H.J. Eom and W-M. Boerner, "Re-Examination of Phase Difference Observed in SAR Imaging of Corn Canopy," IGARSS '87, Remote Sensing of the Terrestrial Underground and the Earth as a System, Ann Arbor, MI, May 18-21, 1987.
- W-M. Boerner, (INVITED KEY-NOTE Speaker), "Basic Principles of Radar Polarimetry and its Applications to Target Recognition Problems," NATO Advanced Study Institute, Electromagnetic Theory and Measurements for Analysis and Synthesis Problems, Pascoli, Tuscany, Italy, August 10-21, 1987.
- B.D. James and W-M. Boerner, (INVITED) "Vector Diffraction Tomography Paraphraphy Using Radar Transform Techniques in Computer-Assisted Electromagnetic Remote Sensing," XXII General Assembly of URSI, Tel Aviv, Israel, Open Symposium on Reconstruction, Imaging and Inverse Scattering, May 1987.
- B-Y. Foo and W-M. Boerner, "Polarization Correction and Extension of Kennaugh-Cosgriff's Target-Ramp Response to the Bistatic Case," XXII General Assembly of URSI, Tel Aviv, Israel, Open Symposium on Reconstruction, Imaging and Inverse Scattering, May 28, 1987.
- A.B. Kostinski and W-M Boerner, "Optimal Reception of Partially Polarized Waves," XXII General Assembly of URSI, Tel Aviv Israel, Open Symposium on Reconstruction, Imaging and Inverse Scattering, May 1987.
- A.B. Kostinski and W-M Boerner, "Formulation of Proper Standards in Radar Polarimetry," Special Session on Measurement Standards: opening paper,

Ninth Annual Meeting and Symposium of the Antenna Measurement
Techniques Association, Seattle, WA, Sept and Oct. 1987.

I.7.6 Invited Seminars/Keynote Speakers
National/International Laboratories

- (Invited) Keynote Overview of the State-of-the-Art of Electromagnetic Inverse Scattering with Emphasis on Needed Mathematical Research," University of Delaware Wkshp. on "Inverse Methods in Electromagnetic Scattering," sponsored by the Naval Air Systems Command, June 11-12, 1985.
- "Recent Advances in Radar Polarimetric Metrology and Vector Signal Processing vs. Azimuth for Multi-(mono/bi)-static Measurement Set-up," research paper presentation at the RAT-SCAT facilities, 6585th Test Group/RX, Holloman AFB, N.M., January 13, 1986.
- "High Resolution Polarimetric Radar Target/Clutter Imaging," invited lecture at the Naval Air Development Center, Warminster, PA., March 24, 1986, Sept. 1987.
- "Recent Advances in Radar Polarimetry and its Immediate Importance to Airborne & Space Surveillance of the Ocean Environment," invited lecture at the Office of Naval Research and the Naval Research Laboratory, Washington, D.C., March 25, 1986, Sept. 1987, Jan. 1988.
- "Electromagnetic Problems and Ocean Wave Imaging," invited lecture at the Institute of Applied Physics, Educational Media Center, University of Tsukuba, Japan, April 7, 1986, March 22, 1988.
- "Polarimetric SAR Imaging," invited lecture at the NASDA, Electromagnetics Division, Tsukuba, Japan, April 9, 1986, March 21, 1988.
- "The Electromagnetic Inverse Problem and Rain Scatter Analysis," invited lecture at the Japan Ministry of Posts & Telecommunications, Radio Research Laboratory, Koganeishi, Tokyo, Japan, April 11/15/22, 1986, March 28/April 11, 1988.
- "Electromagnetic Imaging of Underground/Sea/Ice Objects," invited lecture at the Japan National Institute of Polar Research, Itabashi-ku, Tokyo, June 16 (am), 1986.
- "Interpretation of Polarimetric SAR Imaging," invited lecture at ISAS-Komaba, Remote Sensing Division, Japan, June 16 (pm), 1986, ISAS-Sagamihara, Remote Sensing Div., Japan, April 12, 1988.
- "Polarimetric Radar Meteorology," invited lecture at the Japan Meteorological Research Institute, Tsukuba, June 20 (am), 1986.
- "Detection of Electromagnetic Earthquake Precursor Radiation," invited lecture at the Japan National Center for Disaster Prevention, Earthquake Prediction Division, Tsukuba, June 20 (pm), 1986, March 23, 1988.
- "Polarimetric SAR Image Interpretation," invited lecture at the Ministry of Posts & Telecommunications, Radar Research Laboratory, Remote Sensing Division, Tokyo, July 1, 1986, April 11, 1988.

"Polarimetric Radar Rain Scatter Analysis," Doboku, Kenekyu-Jo
(Ministry of Construction), Flood Control & Severe Weather
Division, Tsukuba, Japan, March 25, April 14, 1988.

Industrial Research Centers

"Inverse Scattering Methods Applied to High Resolution Imaging of
Decomposite Structures," Global Analytics, San Diego, CA, January
17, 1986, Sept. 29, 1987.

"The Electromagnetic Inverse Problem a High Resolution Radar Target
Imaging," Toshiba RDE Center, Kawasaki, April 18, 1986.

"Radar Polarimetry and Satellite Remote Sensing," Mitsubishi
(Kamakura/Ofuna works), Kamakura, April 18, 1986, March 24, 1988.

"Electromagnetic Inverse Problems," Nippon Telegraph & Telephone Co.,
Yokosuka, Electronics Communication Lab., April 23, 1986, March
24, 1988.

"Optical Inverse Problems and High Speed Opto-Electronic Signal
Processing," The Furukawa Electric Co., Chiba, April 24, 1986,
April 13, 1988.

"Optical and Millimeter-Wave Precision Imaging Using Electromagnetic
Inverse Methods," Suzuki Motor Co., Kosai Plant, Shizuoka, May 7,
1986.

"Polarization Perception by Insects, Fish, Eel, Birds, Mammals and
Man," The Japan National Institute for Physiologic Electronic
Sciences, Okazaki, May 9, 1986.

"Use of Millimeter-Wave Radar in Traffic Control," Honda Electronics
Research Center, Toyohashi, May 13 (am), 1986.

"High Resolution M-to-MM-Wave Imaging," Riken EM (Absorbers), Inc.,
Nagoya, May 13 (pm), 1986, April 6, 1988.

"The Electromagnetic Inverse Problems and High Resolution (Precision)
Imaging in the M-to-Sub-MM Wavelength Region," Toyota Research
Laboratory, Nagakuto, Aichi, May 14 (am), 1986, April 6, 1988.

"Applications of Electromagnetic Imaging Methods to Design of
Millimeter Precision Robot Control in Auto-Motion," Brothers,
Industries, Mizukoku, Magoya, May 14 (pm), 1986.

"Electromagnetic Imaging of Underground Obstacles," NCC Musashino
Research Laboratory, Musashino, May 28, 1986.

"High Resolution Polarimetric Radar Imaging," Nippon Electric Company,
NEL Space Development Division, Yokohama, May 29, 1986.

"High Resolution Polarimetric Radar/Ladar Imaging," Furukawa Electric
Co., Opt. Fiber/Integrated Circuits Division, Chiba, June 17,
1986, Central Research Laboratory, Yokohama, April 13, 1988.

"Use of Millimeter-Wave Radars in Traffic Flow Control," Hitachi
Central Research Laboratories, Kokobunji, Tokyo, June 19, 1986.

University Research Centers

- "Optical Inverse Scattering," University of Electro-Communications, Institute for Laser Science (Prof. Hiroshi Takuma), April 12, 1986.
- "Radar Polarimetry," Tokyo Institute of Technology, Tokyo, April 16, 1986, April 12, 1988.
- "Inverse Problems in Geo-Electromagnetism," (with T. Yoshino), Sugadaira Space Research Observatory, UEC, Sugadaira, Tokyo, April 19, 1986, April 8/9, 1988.
- "Early Detection of Electromagnetic Earthquake Precursor Radiation," (with T. Yoshino), Yatsugatake, Japan Earthquake Research Institute, Tokyo University, April 21, 1986, April 8, 1988.
- "Electromagnetic Inverse Problems," Tsukuba Science University, Tsukuba April 25, 1986., March 22, 1988.
- "Polarimetric Perception by Insects, Fish, Birds, Mammals and Man," Toyohashi University of Science & Technology (Toyohashi Gijzu Kago-ku Daigaku), Department of Physiological Electronics, May 7, 1986.
- "Interrelation of Geo-Electromagnetic Earthquake Precursor Radiation and Atmospheric Optic Observatory," Nagoyo University, Research Institute of Atmospherics, Toyokawa, May 8, 1986, April 7, 1988.
- "The Electromagnetic Imaging Problem and the Detection of Buried Obstacles," Tsukuba University of Technology, Toyohashi, May 15, 1986.
- "Electromagnetic Inverse Problems and High Resolution Radar Imaging," Kyoto University, Electromagnetics Department, Kyoto, May 16, 1986.
- "The Electromagnetic Inverse Problem," Osaka University, Department of Electronic Communication Engineering, Osaka, May 19, 1986.
- "Electromagnetic High Resolution Imaging," Osaka Denki Tsushin Daigaku, Osaka, May 20, 1986.
- "The Electromagnetic Inverse Problem," Kyushu University, Fukurawa, invitation by the Japan Institute of Electronics & Communications Engineering, Annual (Tokyo/Kyushu Chapter) Meeting, May 27, 1986.
- "Radar Polarimetry," Denki Tsushin Daigaku, Department of Applied Electronics, Radar Laboratory, Chofu-shi, May 30, 1986, March 29, 1988.
- "Electromagnetic Earthquake Precursor Sensing and Identification," Denki Tsushin Daigaku, Sugadaira Space Radio Observatory, May 31, 1986, March 30, 1988.
- "The Electromagnetic Inverse Problem," Tohoku University, Electrical Engineering Department, Sendai, June 23, 1986.
- "Radar Polarimetry," Morioka University, Electrical Engineering,

Morioka, June 24, 1986.

"The Electromagnetic Inverse Problem," Hokkaido University, Electronic Engineering Department, Sapporo, June 25, 1986.

"Detection of EM Earthquake Precursor Radiation," Akita University, Geology Department, Akita, June 27, 1986.

"Electromagnetic Deep Sounding and Imaging," Niigata University, Electronic Engineering Department, Niigata, June 28, 1986, April 9, 1988.

"The Optical Inverse Scattering Problem," Tokyo Kogyo Daigaku, Opt. Electronics, O-Okoyama, Meguro-ku, June 30, 1986.

"Current State-of-the-Art in Sensing and Detection of EM Earthquake Precursor Radiation," Science Institute, University of Iceland, Reykjavik, Sept. 11-12, 1986, July 24, 1987, Sept. 1988.

Collaborative Academic/Research Interaction Between the University of Iceland and the University of Illinois at Chicago, Faculty of Engineering, School of Engineering, University of Iceland, Reykjavik, Sept. 12, 1986, July 25, 1987.

"The Electromagnetic Imaging Problem," The George Washington University, EECS Dept. Colloquim, Washington, D.C., Feb. 4, 1988.

"The Electromagnetic Inverse Problem," Beijing Institute of Technology, Beijing, P.R. China, April 15-17, 1988.

"Recent Advancements in Radar Polarimetry," Peking University, Beijing, P.R. China, April 20-21, 1988.

"The Electromagnetic Vector Inverse Problem," Qing Hua Daxue, Beijing, P.R. China, April 18, 1988.

"High Resolution Polarimetric Radar Imaging," Xidian Daxue, Xian, Shaanxi, P.R. China, April 25-26, 1988.

"Electromagnetic Inverse Scattering," N.W. Polytechnic University, Xian, P.R. China, April 27, 1988.

"Inverse Problems in Polarimetric Radar Imaging," East China Normal University, Shanghai, P.R. China, April 28, 1988.

"The Vector Inverse Problem in High-Resolution Radar Imaging," Fudan Daxue, Shanghai, P.R. China, April 18, 1988.

1.7.7 Short Courses Given by W-M. Boerner and Associates on Basic & Advanced Radar Polarimetry and Its Applications to Non-Cooperative Target in Clutter Detection, Discrimination, Classification, Imaging and Identification.

Dynalelectron Corporation, Radar Signatures Division, Alamogordo, N.M., one-day course, October 1984.

RAT-SCAT, Radar Backscatter Measurement Facilities, Holloman AFB, one-day course, Oct. 1984, Sept. 1986.

Epsilon Lambda, Millimeterwave Radar Devices and Systems, Geneva, IL,
one-day course, February 1985.

The John Hopkins University, Applied Physics Laboratory, Laurel, MD,
Dec. 1986 (2-day short course).

WEHRTECHNIK Seminare, BMVg/DOD-FRG, BONN, March 1987 (2 days).

NATO-Soc. Mothesime, Paris, Sept. 1986, (4 days).

CCG-DFVLR, Oberpfaffenhafen, FRG, Feb. 1986 (4 days), Jan. 1987 (4
days), Dec. 1987 (2 days), Sept. 1988 (4 days).

NATO-AGARD-ONERA, Paris, May 1987 (4 days).

NASA-JPL, Pasadena, CA./USA, Feb. 1988 (3 days).

NOSC San Diego, CA, March 1988 (2 days).

ISAS-Sagamihara, Japan, April 1988 (2 days).

Ames Research Center, Iowa State University, May 1988 (2 days)

NOAA-ERL-NSSL, Norman, OK, May 1988 (2 days)

CCG-Hamburg, FRG, June 1987 (2 days), Oct. 1988 (2 days)

I.8 HONORS AND AWARDS

- 1985 : Alexander von Humboldt-Stiftung, Senior U.S. Scientist Award, the
Humboldt (Preis) Award, June 21, 1985.
- 1985 : Invited Speaker (JSPS Fellow) on "Electromagnetic Inverse
Problems," International Symposium on Antennas & Propagation of
Japan, ISAS 1985, Kyoto, Japan, 1985 Aug 20 -23
- 1985 : Invited Speaker (CAST Lecture Fellow), International Symposium on
Antennas and Electromagnetic Theory, Beijing, PR China, 1985
August 27 -30
- 1985 : Invited Short Course (CAST Fellow Lecturer), "Electromagnetic
Inverse Methods," Northwest Telecommunications Engineering
Institute, Xian, Shaanxi Province, PR China, 1985 Sept. 3 - 6
- 1985 : Invited Guest Speaker, NATO-AGARD 50th Avionics Panel, Toulouse,
France, 1985 Oct. 14 - 19
- 1986 : Invited Lecturer, CCG-Course: Advanced Radar Polarimetry and the
Applications, DFVLR/CCG, Oberpfaffenhoffen, FRG, 1986, Feb. 4 - 6
- 1986 : Co-Director, Short Course on: Vector Inverse Methods in Radar
Target/Clutter Imaging, ESE, Gif-sur-Yvette, France (Soc.
Mothesim) 1986 Sept. 1 - 5
- 1986 : Invited JSPS-Fellow Lecturer on "Inverse Methods in Electromag-
netic Imaging," and "High Resolution Radar Polarimetry," 1986 March
15 - June 15: Tsukuba Science University, Tokyo Institute of
Technology, Denki Tsushin Daigaku (Univ. of Electro-Comm.),
Toyohashi University of Technology (see 1986 Japan-China Travel
Report)
- 1986 : Invited Senior Scientist CAST Fellow Lecturer on "Inverse Methods
in Electromagnetic Imaging," and "High Resolution Radar

- Polarimetry," 1986 June 16 - July 15, Northwestern Polytechnical University, Xian, PR China, Short Course Lecture Chairman: Xian, Chengdu, Guang Chou (see 1986 China-Japan Travel Report)
- 1987 : US Senior Scientist Fellow Award, Alexander von Humboldt Stiftung, with DFVLR-Oberpfaffenhofen, FRG, 1987 Jan. 1 - July 31 on the "Advancement of Radar Polarimetry"
- 1987 : US Senior Scientist, Norwegian Research Council Fellow, Royal Norwegian Council of Scientific Research, NTNF-PFM, Kjeller, Norway, 1987 May/June
- 1987 : Invited Guest Lecturer (Short-Course by W-M. Boerner), NATO-AGARD /ONERA Short Course on "Radar Cross Section Measurements and Radar Absorbing Materials," 1987 May 3 - 7, Châtillon, France
- 1987 : Invited Speaker, Wehrtechnik Seminar: WT-Sem No 87/0180, 1987 Feb. 19, 20, Multisensorik unter Einbeziehung der Bionik, Radar Polarimetry, Bonn, FRG
- 1987 : US National Academy, Research Council, US Delegate Elect to the General Assembly for the XXIst General Assembly of the Union of Radio Science (URSI), Tel Aviv, Israel, 1987 August 23 - Sept. 6 (URSI Comm. B, C, E and H)
- 1987 : Invited Member, 1987 40th Anniversary Battan Memorial Lecture, Review Panel on Radar Meteorology, Panel "Dual Polarization Diversity Radar Meteorology," Boulder, CO, 1987 Sept. 23/24; 40th Anniversary Radar Meteorology Conference, Boston, MA, 1987 Nov. 10.
- 1987-1988: US Senior Scientist, The Japan Society for the Promotion of Science Fellow, Tsukuba Kagaku Daigaku, Inst. of Optical Physics, Remote Sensing Division (3 months during 1987 Nov. - 1988 July)
- 1987-1988: Invited Committee Member/Session Chairman/Speaker, 1988 Int. Symposium on Radio Propagation, 1988 April 18 - 22, Beijing, China
- 1987-1988: Invited Director, CAST Workshop on Inverse Methods in Electromagnetics, Northwestern Telecommunication Engineering Institute, Xian, PR China, 1988 April 25 - 29
- 1987-1988: Director, NATO Advanced Research Workshops on "Direct and Inverse Methods in Radar Polarimetry," Bad Windsheim, FRG, 1988 Sept. 18-24
- Listings: WHO'S WHO (10): Midwest/Engineering/Education/Eng. Education/Frontier of Technology/Electrical Engineering/North America/International Engineering/International Education/Frontier Science and Technology

I.9 THESIS SUPERVISION

X-Q. (Bill) Huang, "Lambert Mollweide and Aitoff-Hammer projections of the polarization sphere Mercator and its application to radar polarimetry," May 1985.

R.B. Lempkowski, "A modular test bed design of high resolution polarization radar for target in clutter detection and description," May 1985.

Huang, S-M., "Application of Kennaugh's polarization-corrected inverse scattering identity to radar target shape reconstruction based on Radon transformation theory for the limited angle case," May 1986.

Jamés, B.D., "Vector Diffraction Tomography Using Randon Transform Techniques in Computer-assisted Electromagnetic Imaging," March 1987.

M.Sc. Dissertations in Progress

Hallman, J., "Polarimetric SAR Sea/Terrain Image Processing," Spring 1988.

Singh, A., "On Use of Polarization Null Descriptors in Polarimetric SAR Image Interpretation," Fall 1988.

Okeke, J., "Application of Polarimetric Clutter Descriptive Theories to the Interpretation of Rough Sea Data," Fall 1988.

Bruntz, Z., "Application of Optimization Theories in Polarization Radar Theory," Fall 1988.

Walther, M., "Development of Graphical and Visual Methods for Polarimetric Radar Target Clutter Signature Display," Fall 1988.

Soliman, N.A., "Re-interpretation of Inverse Synthetic Aperture Radar Methods in Terms of Fourier-Radon Projection Theory," Spring 1989.

Titles of Ph.D. Theses Supervised by W-M. Boerner

F.H. Vandenberg: On the inverse problem of electromagnetic scattering by rotationally symmetric, perfectly conducting shapes, February 1972.

H.P.S. Ahluwalia: Application of a set of electromagnetic inverse boundary conditions to the profile characteristics inversion of conducting smooth and closed shapes, October 1973.

Y.M. Antar: Electromagnetic beam scattering at a planar interface, Oct. 1975.

M.L.A. Gassend: Holographic measurement of particle fields using local reference beam, October 1976.

S.K. Chaudhuri: Utilization of polarization-depolarization characteristics in electromagnetic inverse scattering, February 1977.

Y.D. Das: Application of concepts of 3-dimensional reconstruction of objects from projections to electromagnetic inverse scattering, October 1977.

A.P. Agrawal: A model-free polarimetric clutter description derived from Kenneough's target characteristic operator theory formulated in coherency matrix notation, May 1987.

B-Y. Foo: Application of the vector extension of Kenneough's transient target impulse response method to 3-dimensional target imaging using high resolution polarimetric radar measurement data, May 1987.

Ph.D. Dissertations in Progress

A.M. Khounsary: Polarimetric radiative transport description of propagation through ensembles of discrete scatterers in inhomogeneous media, Fall 1987.

V.K.S. Mirmira: A reassessment of the target eigen-resonance method and the creeping wave concept in electromagnetic inverse scattering for target shape reconstruction in the umbra region, Fall 1987.

B.D. James: Utilization of vector diffraction tomography in underground object imaging, 1990.

C-Y. Chan: Calibration methods for dual polarization radar metrology, 1991.

J.D. Nespor: Theory and design of a dual polarization doppler radar for meteorological studies, 1992.

R.B. Lempkowski: Design of broadband dual polarization radar imaging system, 1993.

Post-Doctoral Fellows Guided/Visiting Professors Hosted by W-M. Boerner

1982-1986: Dr. J. Richard Huynen, Vis./Adjoint Research Scientist, EECS, UIC (Radar Polarimetry)

- 1982-1984: Dr. Naresh C. Mathur, Visiting Assoc. Prof., EECS, UIC
(Radar Polarimetry)
- 1983-1987: Dr. Arthur K. Jordan, Adjoint Associate Professor, EECS, UIC
(Inverse Methods)
- 1984-1985: Dr. Sujeet K. Chaudhuri, Vis. Assoc. Prof., EECS, UIC
(Inverse Scattering)
- 1985-1986: Dr. Lin, Shi-Ming, Visiting Assoc. Prof., EECS, UIC
(Inverse Scattering & Radar Polarimetry)
- 1985-1987: Dr. Alexander B. Kostinski, PDF, EECS, UIC
(Radar Polarimetry and Ellipsometry)
- 1985-1986: Dr. David W. Carnegie, PDF, EECS, UIC
(Radar Polarimetry)
- 1985-1986: Dr. Masakozu Sengoku, Vis. Assoc. Prof., EECS, UIC
(Microwave Scattering)
- 1985- : Dr. Eugene A. Mueller, Adjoint Professor, EECS, UIC
(Radar Meteorology)
- 1986-1987: Dr. Mitsuro Tanaka, Visiting Assoc. Prof., EECS, UIC
(Inverse Scattering)
- 1987 : Dr. Hollis C. Chen, Vis. Senior Professor, EECS, UIC
(Inverse Scattering and Electromagnetic Theory)
- 1987 : Dr. Amit P. Agrawal, PDF, EECS, UIC
(Radar Polarimetry/Meteorology)
- 1987 : Dr. Bing-Yuen Foo, PDF, EECS, UIC
(Electromagnetic Inverse Scattering)
- 1987-1988: Dr. Helmut Süß, Vis. Res. Sci., EECS, UIC
(Radar Polarimetry)
- 1987- : Dr. Arthur K. Jordan, Adjoint Professor, EECS, UIC
(Electromagnetic Inverse Scattering)
- 1988: : Dr. Yoshio Yamaguchi, Vis. Assist. Prof., UIC-EECS/CL
(Radar Remote Sensing, EM Deep Sounding)

I.10 LIST OF PARTICIPATING SCIENTIFIC PERSONNEL WITH DETAILS

The UIC-EECS/CL has been supported since 1980 to advance mathematical/physical/-electronic/signal processing/metrological methods of high resolution radar polarimetry. A strong research team effort has been established, and especially with the recent joining of Dr. Alexander B. Kostinski (January 1985), we have gained new momentum in addressing this complex set of advanced radar research problems. In addition, we had Dr. David W. Carnegie join us so that our computer data processing component is being strengthened.

Principal Investigator(s)

Dr. Wolfgang-M. Boerner, Principal Investigator
Professor & Director

Continuous supervision and guidance of all research components; responsible for reporting, administration, and overall total research effort.

Recent Honors: IEEE Fellow Grade, "For Advancement in Inverse Methods in Sensing Systems and in High Resolution Radar Polarimetry", Nov. 21, 1983.

JSPS Fellow Award for the "Advancement of High Resolution Radar Polarimetry in

Aeronomy", August 1984.

Alexander von Humboldt-Stiftung (FR Germany), Senior U.S. Scientist Award, the Humboldt (Preis) Award, in recognition of scientific cooperation between DFVLR-Oph. (Dr. Wolfgang Keydel); awarded for a nine month period beginning July 1, 1986. Award granted 6/21/85.

Dr. Hyo J. Eom, Co-Investigator
Assistant Professor & Assoc. Director

Main research responsibility for the advancement of electromagnetic remote sensing theories, metrology and techniques.

Research Scientists (Ph.D. completed)

Dr. Alexander B. Kostinski
Research Physicist & Mathematician

Main research responsibility for advancing analytical mathematico-physical methods and basic electromagnetic wave-dependent signal processing.

Ph.D.: "On Reynolds Number Dependence of Turbulence Intensities in Free Shear Flows", August 1984.

Dr. David W. Carnegie
Research Physicist & Signal Processing

Has been added to the team effort to strengthen computer-numerical measurement data processing.

Ph.D.: "Ferromagnetic and Spin Glass Properties of Transition Metal Alloys", August 1985.

Research Engineers (M.Sc./B.Sc. completed: Bio. data available upon request)

Mr. Brian D. James, Ph.D. (candidate)
Computer Data Processing Engineer

Responsible for supervising UIC-EECS/CL DEC VAX-11/750 Research Computer Processing Facility; to develop complicated large scale computer program algorithms for multi-dimensional vector signal/image processing applications with major emphasis placed on numerical vector diffraction tomography.

M.Sc.: "Vector Diffraction Tomography", March 1987.

Mr. Bing-Yuen (Thomas) Foo, Ph.D., 1987 May
Engineering Scientist

Responsible for high resolution transient electromagnetic measurement data interpretation and development of electromagnetic vector inverse problems.

Mr. Ali M. Khounsary, Ph.D., 1987 October
Engineering Mathematician

Responsible for the development of computer-numerical codes/algorithms, especially for vector radiative transport problems as applied to radar target detection in clutter.

Mr. Amit P. Agrawal, Ph.D., 1987 April
Engineering Meteorologist/Clutter Analyst

Supervision of polarimetric model-independent clutter algorithm development and polarimetric clutter measurement data analysis.

Mr. Vithal K. Mirmira, Ph.D. (candidate)

Mathematical Physicist

Responsible for the development of mathematical models and applicable vector inverse scattering theories.

Mr. Robert M. Lempkowski, Ph.D. (candidate)

Radar Engineer

Responsible for the development of polarimetric radar metrology and specific modular test-bed radar designs.

Mrs. Yan, Wei-Ling, Ph.D. (candidate)

Computer Mathematical Analyst (radar polarimetry)

Mr. Gan, Wei-Nong, Ph.D. (candidate)

Polarimetric radar analysis

Graduate Research Assistants (M.Sc. candidates)

Mr. Xiao-Qing Huang, M.Sc./Ph.D. candidate

Color/Vector Graphics Polarimetric Signal Analyst (assistant to Brian D. James)
Development of color/vector graphic multidimensional vector signal/image processing techniques for polarimetric measurement data analysis.

Mr. Jonas Okeke, M.Sc. 1988 May

Radar Clutter Analyst (assistant to Amit P. Agrawal)

Development of monostatic polarimetric model-independent clutter theory and its computer numerical verification using modelling and measurement data.

Mr. John Hallman, M.Sc. (Diploma) 1987 October

Engineering signal analyst (assistant to Robert M. Lempkowski)

Development of multi-dimensional signal processing modules for modular test-bed experimentation radar.

Ms. Sheng-Ming (Mini) Huang, M.Sc. 1986 December

Engineering Analyst (assistant to Bing-Yuen Foo and Brian D. James)

Development of three-dimensional target reconstruction methods based on Radon back-projection theory using transient ramp response data.

Mr. Matthias Walther, M.Sc. 1988 August

Radar Signal Processing (assistant to Robert M. Lempkowski)

Development of polarimetric doppler and pulse compression techniques for MMW seeker radar development.

Mr. Michael A. Morrill, M.Sc. (Diploma) 1987 May

Engineering Scientist (assistant to Dr. Alexander B. Kostinski and Mr. Ali M. Khounsary)

Development of analytical and computer numerical polarimetric target vs. clutter detection algorithms.

Mr. Nabil Soliman, M.Sc./Ph.D. candidate

Computer Image Processing Analyst

Applications of vector diffraction tomography in biomedicine and electromagnetic deep sounding.

Mr. Rafael Villasuso, M.Sc. candidate

Computer-Numerical/Image Program Analyst (polarimetric radar meteorology)

I.11 DISTRIBUTION LIST

I.11.1 U.S. Department of the Army

Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709
Electronics Division: Dr. James W. Mink (919) 549-0641, Ext. 297
Atmospheric Sciences Division: Dr. Walter Flood (919) 549-0641, Ext. 246

U.S. Army ERAD-COM, CS&TA, Ft. Monmouth, NJ 07703
Radar Division: Dr. Vahakn Nalbandian/Mr. Willie Johnson, DELCS-R-T (201) 544-5148

U.S. Army LAB-COM, Harry Diamond Labs, 2800 Powdermill Rd., Adelphi, MD 20783
Mr. Michael Kokinda, Head, Programs & Planning, (202) 394-3604

U.S. Army ERADCOM, Building 357, Ft. Belvoir, VA 22060
Dr. Roland Wright/Mr. Thomas Witten, Attn: DELNV-AC (703) 664-6267

U.S. Army Missile Command, Redstone Arsenal, AL 35898
AMSMI-REG: Dr. Fred W. Sedenquist (205) 876-8131
DRSMI-REG: Mr. Lloyd W. Root/Mr. Robert Russell (205) 876-8131

U.S. Army Belvoir R&D Center, Ft. Belvoir, VA 22060
Dr. Karl Steinbach, Attn: DRDME-HS (703) 664-4970/2462
Dr. Jack Bond, Attn: STRBE-JD (703) 664-6741

U.S. Army LAB-COM, DA, Harry Diamond Labs, 2800 Powdermill Rd., Adelphi, MD 20783
Radar Physics Section: Dr. Donald E. Wortman, Attn: DELHD-RT-RA (202) 394-2042
Radar Division: Dr. Norman Berg, Dr. Dominique Giglio, DELHD-RT-RA (202) 394-2530
Math/Syst. Analysis Section: Mr. Peter Johnson
Math Sciences Division: Dr. Luther Bergstroem, Division Chief
Microwave Engineering Division: Dr. Joseph Nemarich
Plans & Operations Office: Dr. Stanley Kulpa, Attn: DELHD-PO-P (202) 394-1551
HDL Directorate: Dr. Lou Tozzi, HDL Technical Director

U.S. Army MICOM, DRDMI-TEG/DRDMI-ICBB, Redstone Arsenal, AL 35809

U.S. Army Ballistic Missile Defense Systems Command, Huntsville, AL 35807-1500,
Discrimination Directorate: Mr. Charles D. Johnson (205) 895-3434

U.S. Army Tank Automation Command, AM-STA/NTRE, Warren, MI 48397-5000
Mr. Stephen Adams (313) 574-6505

U.S. Army Atmospheric Sciences Lab, Whitesands Missile Range, NM 88002
Dr. Douglas R. Brown, Attn: DELAS-AR-A (505) 678-3691

U.S. Army Corps of Engineers, Waterways Experiment Station, Environmental Lab,
3909 Halls Ferry Rd., Vicksburg, MS 39180-0631, Mr. Daniel Cress, Mr. Jerry
Lundien (601) 634-2655/2732

Engineering Topographic Labs., CPS-RI Institute, Ft. Belvoir, VA 22060-5546
Dr. Fred Rhode (703) 355-2735

U.S. Army Corps of Engineers, Waterways Experiment Station, Geotechnical Lab,
Earthquake Eng. & Geophys., 3909 Halls Ferry Rd., Vicksburg, MS 39180-0631, Dr.
D. Gus Franklin (601)634-2658

I.11.2 U.S. Department of the Navy

Office of Naval Research, 800 N. Quincy Street, Arlington, VA 22217
Electronics Division: Dr. Kenneth Davis/Dr. Arthur K. Jordan (202)
696-4216/4217

Coastal & Marine Sciences Div., Code 462: Dr. Hans Dolezalek (202) 696-4025
Math. Div., Code 432: Dr. Randolph Simpson (202) 696-4362
Comp. Sci. Div., Code 432: Dr. Charles J. Holland (202) 696-4302
Applied Technology Div., Code 1244: Mr. James G. Smith (202)696-4715

Office of Naval Research, 1030 East Green St., Pasadena, CA 91106
Electronics Division: Dr. Richard G. Brandt (818) 795-5971, Ext. 49

Office of Naval Technology, 800 N. Quincy Street, Arlington, VA 22217
Electronics Div., Code : Dr. Paul Quinn (202) 696-4771

Naval Air Systems Command, Jefferson Plaza #1, Washington, D.C. 20361
Dr. Gerhard Heiche, Code AIR-33M (202) 692-2514
Electr. Research, Rm. 778: Mr. Berry Dillon/Mr. Jim Smith, Code 340J (Ext. 2514)

Naval Sea Systems Command, Crystal Plaza, Rm. 880, Washington, D.C. 20362
Mr. Charles E. Jedrey (202) 692-9760

Naval Electronics Systems Command, Washington, D.C. 20332
Dr. Robert Dupuy, Code 6136 (202) 692-6089/3794

U.S. Naval Research Laboratory, Washington, DC 20375-5000 (US Mail)
4555 Overlook Ave., Washington, D.C., 20032 (Fed. Ex.)

Basic Radar Polarimetric Theory

| | |
|---------------------|-------------------|
| Dr. Merrill Skolnik | Dr. Andy Andrews |
| Dr. Clifford Temes | Dr. Allan Pitty |
| Dr. Dennis Trizna | Dr. Lothar Ruhnke |
| Mr. Jack Daley | Dr. Irving Olin |

Polarimetric Sea Scatter Analysis

Dr. Irving Olin
Dr. Dennis Trizna
Dr. Louis Wetzel
Dr. Gus Valenzuela

Polarimetric High Resolution Radar/SAR-Imaging

| | |
|------------------|----------------------|
| Dr. Andy Andrews | Dr. David Kerr |
| Dr. Allan Petty | Dr. Arthur K. Jordan |

Vector (Polarization) Inverse Scattering Methods

Dr. Arthur K. Jordan
Dr. Lothar Ruhnke

U.S. Naval Air Development Center, Warminster, PA 18974
Street & Jacksonville Roads

Basic Polarimetric Radar Theory

Dr. Charles Haney
Dr. Andy Ochadlick
Dr. Otto Kessler

Polarimetric Radar Target Downrange/Crossrange Imaging

Dr. Otto Kessler
Mr. Jerry B. Polin
Mr. Raymond Dalton
Cmdr. Richard Feierabend

Polarimetric SAR Imaging

Dr. Charles Haney
Dr. Andy Ochadlick
Mr. Otto Kessler
Cmdr. Richard Feierabend

Polarimetric Sea Scatter Analyses

Mr. Raymond Dalton
Dr. Otto Kessler
Mr. Jerry B. Polin

U.S. Naval Weapons Center, China Lake, CA 93555
Knox Road, Bldg. 0005

Vector (Polarization) Inverse Scattering Theory

Dr. Guenter Winkler
Dr. Robert J. Dinger
Dr. Brett Borden

High Resolution Polarimetric Radar SAR/ISAR Imaging

Dr. Stephen Wolf
Dr. David Reade

Polarimetric Radar Meteorology

Dr. Hans Pfeifer
Dr. Robert J. Dinger
Dr. Stephen Wolf

U.S. Naval Ocean Systems Center, San Diego, CA 92152-5000
271 Catalina Blvd.

Basic Polarimetric Radar Theory

Dr. Donald H. Wehner
Dr. David J. Kaplan
Dr. Paul S. Livingston

High Resolution Polarimetric Radar SAR/ISAR Imaging

Dr. R. L. Petty
Dr. Donald H. Wehner

Polarimetric Sea Scatter Analysis

Dr. Juergen Richter
Dr. Donald H. Wehner

U.S. Naval Surface Weapons Center, Dahlgren, VA 22448
Code 7-12, Dahlgren Laboratory

Polarimetric Radar Target/Clutter Analysis

Dr. Bruce Z. Hollmann/703-663-8057

Dr. Ronald Stump

U.S. Naval Coastal Systems Center, Panama City, FL 32407

Code NCSC 4130, EM Division

Basic Polarimetric Radar Theory

Dr. Michael Wynn

ULF/ELF/VLF Polarimetric Signatures of Dielectric/Conducting Objects (Mines)

Submerged in Surf Zones and Shallow Waters

Dr. Michael Wynn

Dr. Lee Frye/904-234-4100/4682

Naval Ocean Research & Development Lab. (NORDA), St Louis, MO 35929-5004

Code 350

Vector (Polarization) Vector Diffraction Tomography Applied to Mine Detection

Dr. Daniel Hickman/601-688-4423

U.S. Marine Corps D&E Center, MCDEC Development Center, Quantico, VA

Polarimetric Radar Technology

Dr. John Druznick

Naval Avionics Center, Indianapolis, IN 46219-2189

Code D-1801-6, 6000 E. 21st St.

Applied Research

Mr. Royal Eckstein/317-353-3311

Defense Advanced Research Project Agency, Naval Technology Office

DARPA-NTO, 4800 Wilson Blvd, ARLINGTON, VA. 22209-2308

Dr. Ronald Repka

Dr. Thomas Taylor

I.11.3 Defense Advanced Research Project Agency

Defense Advanced Res. Project Agency, 1400 Wilson Blvd., Arlington, VA 22209

Radar Polarimetry, TTO: Lt. Col. Juergen Gobien (202) 694-2612

Massachusetts Inst. of Techn., Lincoln Lab., P.O. Box 73, Lexington, MA 02173,

Drs. George H. Knittel/Gregory Heath/Richard M. Barnes (617) 863-5500

I.11.4 U.S. Department of the Air Force

Office of Scientific Research, AFOSR/NE, Bldg. 410, Bolling Air Force Base, DC 20332

Electronics/Materials Division: Dr. Horst Wittmann (202) 697-4931/4933

Rome Air Development Center-East, Hanscom Air Force Base, MA 01731

EM Sciences Division: Dr. Allan C. Schell/Dr. Robert Papa (617) 369-4000, Ext. 297

Rome Air Development Center, Griffis Air Force Base, Rome, NY 13441-5700

Dr. Clarence Silfer/Dr. Vincent Vannicola (315) 330-4431/4437

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Air Force Avionics Laboratory, Wright-Patterson Air Force Base, OH 45433
Mr. Allen Blume AFWAL/AADM; Dr. Medhi Shirazi (513) 255-6427/Dr. J. Earl Jones
AFWAL/AARM-1 (513) 755-4202; Dr. J.C. Ryles AFWAL/AS (513) 255-3627
(also Codes: AFWAL/AAWP-3, ATWAL/AAAN, AIWAL/AAR1-665A: 513-255-6141; ASD/RWEA:
513-255-2420; ASD/RWQC: 513-255-6274)

Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, NM 87117
Dr. Karl Baum (505) 844-0601

RAT-SCAT Whitesands Missile Range, P.O. Box 541, Holloman Air Force Base, NM
88330, Capt. David Stein (505) 679-3120/3129/Mr. Stanley Shaw (505)
434-3645/3525, HQ USAF/RDQ, The Pentagon, Washington, D.C., 20330-1000

I.11.5 Academic Research Institutions

University of Illinois at Urbana-Champaign, ECE, Applied Electromagnetics
Laboratory, Urbana, IL, Drs. Yuen-Tsien Lo, Shung-Wu (Andy) Lee, Georges A.
Deschamps, (217) 333-1200

The Ohio State University, ElectroScience Lab., 1430 Kinnear Rd., Columbus, OH
43212, Drs. Jonathan D. Young/Eric Walton/Leon Peters, Jr. (614) 422-6657/5051

Georgia Institute of Technology, Radar & Instrumentation Lab, Atlanta, GA.
30332, GTRI Electr. & Radar Divs: Drs. Gerry L. Eaves/Wm. Hold/E. Otto Rausch
(404) 424-9609

University of California, Lawrence Livermore Labs, Box 808, Livermore, CA 94550
Drs. Hriar Cabayan/Robert Bevensee (415) 422-8871

SANDIA National Laboratory, Electromagnetic Div., Sect. 1651, Albuquerque, NM
87185, Attn: Dr. Jiunn S. Yu, Senior Scientist, (505) 844-6727

I.11.6 Procurement Offices

Department of the Army, U.S. Army Research Office, 4300 S. Miami Blvd., P.O. Box
12211, Research Triangle Park, N.C. 27709-2211. +1(919)549-0641, Attn: Mr. Jack
Harless x267, Info. Processing Office, Mr. Richard O. Ulsa, x218.

Department of the Navy, Office of Naval Research, Chicago Branch Office, 536 S.
Clark St., Rm. 286, Chicago, IL 60605-1588, Attn: Mr. Gordon I. Lovitt, Mr.
John Michalski +1(312)886-5421.

University of Illinois at Chicago, Office of Business Affairs, Office of Grants
and Contracts, 176 PHARM (m/c 155), 833 S. Wood St., Chicago, IL 60680-4348,
Attn: Mr. John P. Ward, +1(312)996-5859; Mr. Glenn Meeks, +1(312)996-2862.

PART II: IMPORTANT ATTACHMENTS

In order to sample the breadth and quality of our research output, the following reports, keynote addresses, and copies of publications have been attached to this report.

II.1 Research Travel Report Summaries

- II.1.A W-M. Boerner, JSPS CAST US Senior Scientist Fellowship Japan/China Research Travel Report (1986 August 15): Advancement of Science & Technology in High Resolution Radar Polarimetry Using Electromagnetic Inverse Methods, Phase I: 1986, March 23 to 1986 July 23
- II.1.B W-M. Boerner, Report on Sabbatical Research Leave as Alexander von Humboldt US Senior Scientist Fellow Award (1988 May 31): The Advancement of Inverse Methods in High Resolution Polarimetric Target Imaging in an Air/Land/Sea Clutter Environment, WQ/SQ-87: 1987 Jan. 01 to 1987 July 31
- II.1.C W-M. Boerner, JSPS/CAST US Senior Scientist Fellow Award (1988 May 31): Advancement of Science & Technology in High Resolution Radar Polarimetry Using Electromagnetic Inverse Methods, Phase II: 1988 March 14 to 1988 April 30.

II.2 Recent Publications in Refereed Journals (1985 Jan. to 1988 August)

- II.2.1 A.B. Kostinski and W-M. Boerner, "On Foundations of Radar Polarimetry," accepted for publication in the IEEE Transactions on Antennas & Propagation, Vol. AP-34, No. 12, pp. 1395-1404, also see: comments by H. Mieras, pp. 1470-1471, and Author's Reply, pp. 1471-1473, Dec. 1986.
- II.2.2 M. Davidovitz and W-M. Boerner, "Extension of Kennaugh's Optimal Polarization Concept to the Asymmetric Scattering Matrix Case," accepted for publication in the IEEE Transactions on Antennas & Propagation, Vol. AP-34, No. 4, pp. 569-574, April 1986.
- II.2.3 W-M. Boerner, B.-Y. Foo, H.J. Eom, "Interpretation of the Polarimetric Co-Polarization Phase Term ($\phi_{HH} - \phi_{VV}$) in High Resolution SAR Imaging Using the JPL CV-990 Polarimetric L-Band SAR Data," submitted for publication in the Special IGARSS'85 Issue of the IEEE Transactions on Geoscience & Remote Sensing, Vol. GE-25, No. 1, pp. 77-82, Jan. 1987.
- II.2.4 A.B. Kostinski and W-M. Boerner, "On the Polarimetric Contrast Optimization," IEEE Trans. A&P, Vol 35(8), pp. 988-991, Aug. 1987.
- II.2.5 Lin, S.M. and W-M. Boerner, "On the Discrete Radon Transform," J.N.W. Polytechnical Univ., Vol. 6, No. 2, pp. 173-180, April 1988.
- II.2.6 A.B. Kostinski, B.D. James, and W-M. Boerner, "On the Optimal Reception of Partially Polarized Waves," J. Optical Society of America, Part A, Optics & Image Sciences, Series 2, Vol. 5(1), pp. 58-64, Jan 1, 1988.
- II.2.7 A.P. Agrawal and W-M. Boerner, "Description of Polarimetric Backscatter Radar Model for Distributed Scatterers for the Partially Polarized Case," Radio Science, (subm. October 1986, acc. Aug. 1987), Nov. 1988.
- II.2.8 Eom and W-M. Boerner, "A Re-examination of Radar Terrain Backscattering at Nadir," IEEE Transactions on Geoscience & Remote Sensing, vol. GE-24, No. 2, pp. 232-234, March 1986.
- II.2.9 H.J. Eom and W-M. Boerner, "Scattering from a Layered Medium Connected

With Rough Interfaces: Matrix Doubling Method," IEEE Trans. Geoscience & Remote Sensing, Vol. GE-24, No. 6, pp. 937-939, Nov. 1986.

- II.2.10 A.P. Agrawal and W-M. Boerner, "Re-Development of Kennaugh's Characteristic Polarization Theory Using the Polarization Transformation Ratio Formalism for the Coherent Case," IEEE Trans. on Geoscience Electronics, (subm. Oct. 1986, acc. Nov. 1987), October 1988.
- II.2.11 A.B. Kostinski, B.D. James and W-M. Boerner, "Polarimetric Matched Filter for Coherent Imaging," Canadian Journal of Physics, Special Issue on Optics and Modern Image Processing, (subm. Jan 1988, acc. April 1988, to appear Dec. 1988).
- II.2.12 A.B. Kostinski, B.D. James and W-M. Boerner, "The Polarimetric Matched Image Filter and its Application to POL-Sar Image Analysis," IEEE Trans. AES, (subm. March 1988, acc. May 1988, to appear Nov. 1988).

II.3 Invited Lectures & Keynote Addresses at International Conferences

- II.3.1 W-M. Boerner, "Electromagnetic Inverse Methods - A State of the Art Review," IEEE/APS-Section Tokyo, IECE of Japan, Sect. A&P, Vol. 86-20, pp. 71-77, May 1986.
- II.3.2a W-M. Boerner, (INVITED) "Recent Advances in Radar Polarimetry - Current State of the Art," Fifth Int. Conf. on Antennas and Prop., ICAP 1987, Univ. of York, UK, March 30 - April 2, 1987, Proceedings, Part II, pp. 2.359 - 2.363.
- II.3.2b W-M. Boerner, (INVITED), "The Electromagnetic Inverse Problem - Current State of the Art," Fifth Int. Conf. on Antennas and Prop., ICAP 1987, Univ. of York, UK, March 30 - April 2, 1987, Proceedings, Part I, pp. 1.462 - 1.466.
- II.3.3 A.P. Agrawal, D.W. Carnegie, and W-M. Boerner, "Evaluation of Dual Polarization Scattering Matrix Radar Rain Scatter Measurements in the X and Q-Band," Fifth Int. Conf. on Antennas and Prop., ICAP 1987, Univ. of York, UK, March 30 - April 2, 1987.
- II.3.4 A.P. Agrawal, H.J. Eom and W-M. Boerner, "An Analysis of Polarimetric (VV, HH, & VH Polarized) Scattering Matrix Data of Near-Grazing Sea Backscatter at X-Band," Proceedings of the 4th Working Symposium on Oceanographic Data Systems, Scripps Institution of Oceanography, LaJolla, CA, 11 pp. 39-49, Feb. 4-6, 1986.
- II.3.5a S.K. Chaudhuri and W-M. Boerner, "Multi-(Bi)-Static High Frequency (PO/GO) Radar Target Imaging of Airborne Scatterers," NATO-AGARD Conference Preprint No. 381, Multifunction Radar for Airborne Applications, pp. 27-1 thru 27-11, Avionics Panel Symposium, Toulouse, France, Oct. 14-18, 1985.
- II.3.5b B-Y. Foo, S.K. Chaudhuri and W-M. Boerner, "Basic Monostatic Polarimetric Broadband Target Scattering Analysis Required for High Resolution Polarimetric Radar Target Downrange/Crossrange Imaging of Airborne Scatterers," NATO-AGARD Conference Preprint No. 381, Multifunction Radar for Airborne Applications, pp. 26-1 thru 26-9, Avionics Panel Symposium, Toulouse, France, Oct. 14-18, 1985.

II.4 International Workshop Lecture Series by W-M. Boerner et al.

- II.4.1 CCG-DFVLR, Oberpfaffenhofen, FRG, Feb. 1986 (4 days), Jan. 1987 (4

days), Dec. 1987 (2 days), Sept. 1988 (4 days).

II.4.2 NATO-Soc., Mothesime, Paris, Sept. 1986, (4 days).

II.5 International Workshops Coordinated, Directed/Co-directed by W-M. Boerner

II.5.1 NATO-ARW-DIMRP '88 on Direct & Inverse Methods in Radar Polarimetry, KuK
Residenz, Bad Windsheim, FRG, September 18-24, 1988 (Director).

II.5.2 Third Polarimetric Technology Workshop, Redstone Arsenal, AL, August
16-18, 1988 (Member of Planning Committee, Chairman of Session 4 and
NATO Session).

Nationality: USA

Name: BOERNER, Wolfgang - Martin

Date: 1986, August 15

THE JSPS FELLOWSHIP FOR RESEARCH
IN JAPAN

RESEARCH REPORT

(submitted: 1987 January 09)

Host Scientist: Prof. Fujimoto, Kyohei

Research Period: From 1986, March 23 To 1986, July 23

Title of Research in Japan: PHASE I: Advancement of Science & Technology
in High Resolution Radar Polarimetry Using
Electromagnetic Inverse Methods

Signature: Wolfgang-M. Boerner
Dr. Wolfgang-M. Boerner

- * Submit a research report to JSPS within 1 month after termination of your fellowship in Japan.



10
THE
UNIVERSITY
OF
ILLINOIS
AT
CHICAGO

Communications Laboratory (M/C 154)
Department of Electrical Engineering and Computer Science
4210-4211 Science and Engineering Laboratories
Box 4348, Chicago, Illinois 60680 U.S.A.
(312) 996-5480/5140

1986 Jan. 09

Dr. Kyohei Fujimoto
Inst. of Applied Physics
University of Tsukuba
Sakura-mura, Ibaraki-ken 305
Japan

Dear Kyohei:

First of all thank you for your many letters reminding me of my bad conscience in not having the FINAL REPORT completed.

Now, finally, enclosed please find the FINAL DRAFT MANUSCRIPT of my Final Report which still will require additional extensive modifications over the next months to come. Because of the tremendously broad scope of my Phase I JSPS/CAST tenure, much more time than usually required, was needed. It is plainly impossible to prepare a meaningful FINAL REPORT after only one month, and I invite your understanding of these important facts.

You will observe from an inspection of this material that I have sincerely enjoyed my stay in Japan and that you have turned me into a sincere admirer and friend of Japan.

Under the very great stress and time pressure I was suffering since my return from the Northwest Pacific Orient, you must consider it like I do: A real unexpected wonder that I got it almost done today.

By copy of this letter to my co-hosts, Professors Yasumitsu Miyazaki, Takeo Yoshino and Lin, Shi-Min and our administrative benefactors Mrs. Yoki Furukawa, Dr. Annette M. Johnke, Dr. Richard G. Brandt, Prof. Huang Zhong-zheng, Dr. James W. Mink, and Dr. George B. Wright as well as to my department head and deans, Dr. Wai-Kai Chen (JSPS-fellow 1987) and Dr. Paul M. Chung and Dr. Ronald P. Legon, I wish to express my sincere thanks to everyone involved for making possible this most inspiring research travel to the Northwest Pacific Orient.

Looking forward with great enthusiasm to my Phase II engagement during early 1988.

Sincerely yours

Wolfgang-M. Boerner, Ph.D.
Professor and Director

cc. Prof. Takeo Yoshiro
Prof. Yasumitsu Miyazaki
Prof. Lin, Shi-Ming
Mrs. Yuko Furukawa
Dr. Annette M. Johnke
Dr. James W. Mink
Dr. George B. Wright
Dr. Richard G. Brandt
Dr. Arthur K. Jordan
Dr. Wai-Kai Chen
Dr. Paul M. Chung.

Attachment

RESEARCH REPORT
(1986 August 15)

THE JSPS FELLOWSHIP FOR RESEARCH IN JAPAN

prepared by: Dr. Wolfgang-M. Boerner
(JSPS Fellow) Professor & Director
UIC-EECS/CL (M/C 154)
840 W. Taylor St. SEL-4210
Chicago, IL/USA 60680-4348
1-312-996-5480/5140

Wolfgang-M. Boerner
1986 Feb 08.

Title: Advancement of Science & Technology
in High Resolution Radar Polarimetry
Using Electromagnetic Inverse Methods

Program Phasing: The research collaboration of this JSPS Fellow
with his three Japanese Host Scientists is spread
over many years and separated into three major
phases. Here, we are reporting on the RESULTS of the
First Phase which was subdivided into four parts
including a visit to NPU Xian, China for current and
future enrichment of the program.

Duration: PHASE I: 1986, March 23-to-July 23
Ph.I, Part 1:1986, March 23-to-April 25/TUS:Prof. K. Fujimoto
Ph.I, Part 2:1986, April 26-to-June 03/TUT:Prof. Y. Miyazaki
Ph.I, Part 3:1986, June 04-to-July 01/UEC:Prof. T. Yoshino
Ph.I, Part 4:1986, July 02-to-July 23/NPU:Prof. Lin, Shi-Ming

Host/Inst: Prof. Kyohei Fujimoto, Tsukuba University of Science
Tsukuba Kagaku Daigaku, Inst. Applied Physics
Sakura-mura, Ibaraki-ken 305, Tel 81-298-53-2435/5313

Collaborating Institutes:

| | | |
|--------------------------------|----------------------|----------------------|
| Co-Host Inst:TUT | Co-Host Inst:UEC | Co-Host Inst:NPU |
| Toyohashi Gijutsu | Denki Tsushin | Northwestern Poly- |
| Kagaku Daigaku | Daigaku | technical University |
| Tempaku-cho, Toyohashi-shi 440 | Chofu-shi, Tokyo 182 | Xian, Shaanxi China |
| 81-532-47-0111x528/574 | 81-424-832161x3351 | 86-29-51491 |

Summary: Attached to this title page

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A-2. List of Contact Addresses

III. Research Travel & Cultural Activities

IV. Recommendations & Suggestions

V. Acknowledgements

Phase I

Summary: My Phase I (1986, March 23 to July 23) engagement as a JSPS Fellow from the USA in Japan was a most rewarding experience due to the very dedicated attention given to me by my three hosts who opened up so many academic, scientific, cultural, social and religious windows for me to become an everlasting friend of the Japanese people, a stound admirer of their multi-varied accomplishments and a fellow-struggler for the beautification of their cities and the improvement of their rich marine/coastal/land/mountain islands' environment. Although it has been a rather short visit by number of months, weeks and days, it was a most efficient and rewarding time thanks to the well groomed Japanese punctuality, correctness, preciseness and dedication of getting things done at the best of one's abilities. My three hosts, all three so different in character, scientific approach, scope, highly talented, innovative, unique personal interests and hobbies, made it possible because of their rather striking different approach to academic and research guidance for me to obtain a rather rare glimpse behind the curtains of strict formality which so much can obscure a real vision of Japan. I was able to observe a lot, to deliver many lectures, to return with many new ideas and, above all, with the confidence of having made many new long lasting friendships out of which productive research innovation will result.

Before concluding with this executive summary, I wish to emphasize the importance of visiting both Japan and the Oriental Continent (Korea, China, Taiwan) whenever, we "occidentals" visit the Orient in order to obtain a deeper appreciation of the diversification but also, unique similarities of these countries; and thus I was very grateful that a short visit to the Universities of Xian, and particularly of NPU, was approved by JSPS to be included in my research travel program.

This Phase I (Final) Research Report consists of five major Chapters and two major attachments: In Chapter I (2 pages) the historical background leading to the JSPS/CAST invitations is laid out; in Chapter II (four parts: 25 pages) the Research Programs and Interactions with the four host institutions are summarized; in Chapter III (four parts: 24 pages) research and cultural travel are highlighted; in Chapter IV (7 components: 7 pages) major recommendations for program improvements are suggested; and in Chapter V acknowledgements are added. The attachments consist of the Time/Travel Schedules (A.1) and the List of Contact Addresses (A.2).

I. BACKGROUND AND HISTORICAL DEVELOPMENT OF MY PERSONAL INTERACTIONS WITH THE ORIENT: CHINA, TAIWAN, INDONESIA, KOREA AND JAPAN

1.1 Childhood in Austral-Asia

As a native of Papua-New Guinea (born: Finschhafen, Morobe District: 1937 July 26), survivor of the Japanese and US Naval counter-attacks on Guadal Canal, Solomon Islands (1941 to 1943), internment in ANZ (1944-1947)-POW camps, and the raging battles of the Kou-Min-Dang versus Gung-Ysan-Dang forces (1948/49) in Kanton (Guang-Zhou, Guang-Dong) and the liberation of Indonesia (1947/48); W-M. Boerner's child/boy-hood history, as son of a Lutheran Mission agriculturist, was and is still closely involved in the cultural/scientific/technological developments of the Austral Pacific and Pacific Orient, particularly Austral-Asia, Indonesia, China and increasingly more with Korea and Japan. During my childhood in Guadal Canal (1941-44) and boyhood in the internment camp Rushworth III/Tatura, Victoria, I had ample opportunity to interact at a young age with Japanese which had fascinated me and further strengthened my desires to visit Japan and to become familiar with its country, culture, society and people.

1.2 Previous Travels by W-M. Boerner to Japan

During my studies at the Technische Universität München, the University of Pennsylvania in Philadelphia and at the University of Michigan in Ann Arbor, I was fortunate to meet with many impressive Japanese co-graduate students, post-doctoral fellows and visiting scientists who intrigued me to visit Japan as soon as possible. Then during my post doctoral year (1968/69) at the University of Manitoba, Winnipeg, Canada I met with Mr. Masami Iwasaki, M.B.A., and Mr. Takao Namiki, M. Sc. EE, of Furukawa Electric Co., who was a post-graduate student of Professors Toshio Sekiguchi and Yasuharu Suematsu both of Tokyo Kogyo Daigaku (Tokyo Institute of Technology); and he together with Masami and their families opened many doors to the Japanese way of life for me.

Since 1969, Dr. W-M. Boerner conducted seven major research travel to the Pacific Orient and Austral Pacific including visits to the Arctic (Alaska/Behring Strait), Japan (five times), Korea, P.R. China, Taiwan, Hong-Kong, Indonesia, Philippines, Australia, New Zealand and Antarctica. In 1970, he visited Japan together with his wife Eileen-Annette, for the first time being guest of the family Namiki; visiting Prof. Toshio Sekiguchi, Tokyo Kogyo Daigaku and Prof. Mikio Namiki, Waseda University for the first time and establishing many friendships, including that with Dr. Kyohei Fujimoto of Matsushita Electric Company. He has since participated in all of the three "International Symposia on Antennas and Propagation (ISAP)" of Japan in 1971 (Sendai), 1978 (Sendai) and 1985 (Kyoto), where he greatly expanded his existing base of scientific contacts and especially he became friends of Prof. Yasumitsu Miyazaki (1971) and Prof. Takeo Yoshino (1978) and many more. During these important scientific events (ISAP 1971/78/85), he established close research collaboration with many Japanese research institutions of academia, industry and government with the desire to revisit Japan on a periodic basis at about every two to five years.

1.3 Formal Invitation to Visit China and Japan as Fellow of the Academia Sinica (CAST) and of the Japan Society for the Promotion of Science (JSPS).

Upon the kind invitation of Professors Kyohei Fujimoto, Toshio Sekiguchi, Yasumitsu Miyazaki, Takeo Yoshino, Saburo Adachi, Kiyohito Itoh and others, a proposal for a JSPS fellowship for Prof. W-M. Boerner was put forth in early 1984 which then was approved in August 1984. Similarly, an invitation by the China

Academy of Science and Technology to visit Xian Shaanxi Province (1985) was approved. Due to the very heavy research contract involvement, Professor Boerner had to defer all visits until the Spring of 1986, as outlined in the next chapter.

Here, it is worthwhile to reemphasize that for a European or North American of Caucasian descent any visit of the Pacific Orient should include both the Japanese Islands and/or Taiwan plus the continent with P.R. China and Hong-kong and/or Korea in order to obtain a well balanced view of the oriental sphere of life. In all of my travels in the Orient, I have strictly adhered to this set goal of mine which is being further interpreted in the following chapters.

Another equally important point in the planning of research interactions with non-US American countries is to strike a balance between my strong research ties developed in Europe, Austral-Asia/Pacific Orient, India/Africa and Southern America which immediately creates severe time constraints on choice and lengths of stay for any international research collaboration. Therefore, it is found expedient to distribute the time spent between Europe, the Austral-Asia/Pacific Orient, South America and India/Africa at about equal shorter reoccurring one-to-three months visits spread over many years.

II. JSPS/RESEARCH PROGRAM DESCRIPTIONS WITH RESEARCH SUMMARIES

2.0 Overall Program Structuring

Because I was given National Fellowship invitations almost for the same period of time by National Societies for the Promotion of International Science Collaboration of Japan, China, Africa, India and Europe (FRG/NO/UK/FR), a very selective choice had to be made under the prevailing constraints of US National State Institutions of Post Higher Education such as the University of Illinois at Chicago which is limited to about three (3) months per two years. I was finally given the go-ahead to accept the invitations from the Pacific Orient with the stipulation of visiting both China and Japan and returning to the UIC campus for one week per calendar month for the following reasons:

(1) On behalf of the UIC-MUCIA engagement of developing close academic and research ties with the Pacific Orient, expend every effort for establishing triangular interactive exchange agreements with China (PRC), Japan/Korea and Northern America.

(2) In order to keep abreast with the research contract monitoring of ongoing large-scale research projects a monthly contract review at UIC, the contract research offices in Washington/Huntsville, and at the governmental/industrial R & D Engineering Centers must be included in any international collaborative research agreement.

These fundamental stipulations forced me to subdivide my overall research stay in the Pacific Orient into three major phases of about four parts each. An overall program duration of about four months for the first phase toward carrying out the JSPS and CAST Fellow Award Commitments were granted by the UIC administration and my sponsoring research contract offices with the following program sub-phasing:

Phase I: Japan/China Research Interaction: 1986, March 23 - July 25,
Overall Hosts:

JSPS: Prof. Kyohei Fujimoto, Inst. of Applied Physics, Tsukuba Univ. of Science.

CAST: Prof. Liu, Yuanyong, Vice President, NPU Xian, Shaanxi, China

Phase I: Part I Tsukuba University of Science (TUS): 1986, March 23 - April 25

| | |
|-----------------------------------|---------------------|
| TUS & Host: Prof. Kyohei Fujimoto | April 24 - April 25 |
| UIC-Preparations: | March 24 - March 29 |
| Tsukuba Research Interaction: | March 30 - April 25 |

Phase I: Part II Toyoashi University of Technology (TUT):
1986, April 26 - June 4

(Co-Host: Prof. Yasumitsu Miyazaki)

| | |
|---------------------------|------------------|
| UIC-Preparations: | April 25 - May 1 |
| TUT-Research Interaction: | May 2 - June 4 |

Phase I: Part III Chofu-Shi, University of Electro-Communications:
1986, June 4 - July 1

(Co-Host: Prof. Takeo Yoshino)

UIC-Preparations: June 4 - June 11
UEC - Research-Interaction: June 12 - July 1

Phase I: Part IV China-Japan-UIC Research Collaboration

(Japan-Host: Prof. Kyohei Fujimoto, XIAN-Host: Prof. Lin, Shi-Ming)

TUS-Preparation: July 2 - July 6
XIAN Research Interaction: July 7 - July 12
TUS/UEC/TJT-close Down: July 13 - July 15
UIC-Program Close-Out: July 16 - July 23

During these four parts of Phase I, Dr. W-M. Boerner accomplished a very tightly scheduled research travel program as outlined in all detail in the attached material.

Appendix I: Final Travel/Lecture Itinerary for the JSPS/CAST
Fellow Award Program

Appendix II: List of Research/Social Contacts Made by Dr. W-M. Boerner
during his JSPS/CAST Fellow Award Tenure

In closing this overall Section, it should be noted that Dr. W-M. Boerner was not staying during a particular part of Phase I only at the host institute of the specific interaction period, but was interacting dynamically with all participants at various locations.

Therefore in the next Sections, the integrated research interactions with the particular host institution are provided.

2.A RESEARCH INTERACTION AT TSUKUBA UNIVERSITY OF SCIENCE (TUS): TSUKUBA KAGAKU DAIGAKU

(Because most time at TSUKUBA KAGAKU DAIGAKU was spent during Phase I, Part I, and because Prof. Kyohei Fujimoto not only kindly agreed to serve as the overall coordinator but also the main driving force in obtaining the prestigious JSPS Fellow Award, interactions with him and his able colleagues are presented first).

HOST INSTITUTION I

Research Institute:

Tsukuba Science City
University of Tsukuba
Institute of Applied Physics (IAP)
Educational Media Center (EMC)
Sakura-mura, Ibaraki-ken Japan 305
Telex: 3652 580 (UNITUKUJ)

Host/Coordinator:

Prof. Kyohei Fujimoto, Director

Phone Nos.

EMC: 81-298-53-2435 (AM)

IAF: 81-298-53-5313 (PM) / 2111 (main)

Home: 81-298-57-3378

Junior Professor:

Dr. Kazuhiro Hirasawa 81-298-53-5315

Research Plans:

1. Developement of integrated micro/mm wave circuitry for polarimetric micro-strip-type surveillance/imaging array antenna systems.
2. Simultaneous optimization of antenna gain/directivity/side-lobe reduction/signal to noise performance vs. RCS matrix reduction.
3. Developement of MMW polarimetric pulse compression radar systems applicable to vehicle crash avoidance and vehicle traffic control radar.

Collaboration with Staff and Students

During most of my stays at Tsukuba, the instructional program was at recess, most staff members were on travel, and I was able mainly to interact with Professors Kyohei Fujimoto and Kazuhiro Hirasawa as well as with their talented graduate students of which Mr. Zhang, Yi-Min and Mr. Osana Kawabata impressed me deeply. Mr. Zhang, Yi-Min, a visiting scholar from the NW Telecommunication Engineering Institute in XIAN, Shaanxi Province, P.R. China, is one of the most talented and gifted students I have ever met and it was a real pleasure to work together with him and his very able supervisors. I was also strongly impressed by the computer-numerical mocrrostrip antenna research analyses of Prof. Hirasawa, who had always been very helpful.

The overall research facilities as well as the academic research staff are excellent and a wide scope of diverse fields in Applied Physics was covered. Here, I wish to recall discussions with Prof. Tamon Inouye on his research in Radon projection tomography and the use of Chebycheff limited transform synthesis of object functions with applications to transmission and emission tomography.

Research Lectures:

Fundamentals of Radar Polarimetry
Radar Signal Processing
Radar Target Imaging

Research Publications:

1. W-M. Boerner, Electromagnetic Inverse Methods - A State-of-the Art Review (invited): IEEE/APS-Section Tokyo. Publ:Technical Committee Report. Institute of Electronics & Communications Engineering of Japan, 1986 May 22, Section A&P, pp. 86-20. pp. 71-77.
2. K. Fujimoto, W-M. Boerner, K. Hirasawa, On the developement of polarimetric null beam steering antenna design principles, to be publ. in IEEE Trans. Ant. & Propaq. by 1988 (in preparation).
3. K. Hirasawa, W-M. Boerner, K. Fujimoto, On the developement of numerical (moment) method solutions for optimum design of polarimetric null beam steering antennas (in preparations).

Interactions with Neighboring Research Institutes

Tsukuba Science City provides a splendid research environment, and various specific research problems of mutual interest were discussed with:

- a. NASDA, Tsukuba Space Center, Specific Equipment Laboratory,
2-1-1 Sengen, Sakura-mura, Niihari-gun, Ibaraki-ken 305.
Attn: Dr. Eng. Hiroshi Uda, Director, TSC.
Dr. Eng. Hideo Hishida, Senior Eng.
Dr. Eng. Yasuyuki Itoh, Res. Eng.

Topic: Polarimetric SAR imaging for the Space surveillance of the ocean environment.

- b. MITI. AIST/ETL
Electrotechnical Laboratory
1-1-4 Umezono, Sakura-mura, Niihari-gun, Ibaraki-ken, 305.
Attn: Dr. Eng. Ichiro Yokoshima, Chief, Radio Electronics Section.
Dr. Eng. Koji Komiyama, Res. Eng.

Topic: Detection of oil-spills in an ocean environment from air/space-born platforms using polarimetric radiometry, scatterometry and SAR techniques.

- c. STA, Ntl. Japan Meteorological Research Institute
1-1 Nagamine, Yatabe-machi
Tsukuba-gun, Ibaraki-ken, 305

Radar Meteorology: Dr. Jino Aoyagi
Dr. Masahito Ishihara

Geophysical Meteorology: Dr. Hiroshi Ueda

Topic: Polarimetric Doppler Radar Meteorology
(Polarization Diversity Radar
Applications to Meteorology)

Seismology & Vulcanology: Dr. Toshio Mori
Dr. Seiya Ueda

Topic: Earthquake Prediction Research
(Underground electric potential variation measurements)

- d. STA, Natl. Japan Research Center for Disaster Prevention
3-1 Tennodai, Sakura-mura
Niihari-gun, Ibaraki-ken 305

Earthquake Prediction Division: Dr. Ryosuke Hirobe
Dr. Norio Yoshida
Dr. Shozo Matsumura
Dr. Masakazu Ohtake

Topic: Earthquake Precursor Radiation Research
Electric Storm Schumann Resonances

- e. Tsukuba Botanic Garden
4 Amakubo, Sakura-mura
Nihari-gun, Ibaraki-ken 305

Plant Taxonomy Division: Dr. Tamotsu Hashimoto
Senior Curator

Topic: Wild Flowers of Japan
(J. OHWI, Flora of Japan, translation by Smithsonian)
Ayame, Hanashobu, Kakitsu-bata (Iris Exhibition)

2.7 The Campus of Tsukuba Kagaku Daigaku

The campus of the TUS is only about twenty years old and like the entire Tsukuba Science City, is designed in a rather non-Japanese modernistic architecture which lends a rather artificial, cool social atmosphere to the place. The grandious layout stretched linearly over a mile will require many additions over the next decades to come to round off the campus scenery and thus make it a more friendly place. Yet, given another decade, once the trees, shrubs and woods have grown to their mature size, and more active social life is created, TUS may become a very pleasant campus, provided that at the same time peace of mind finds a resting place in the Tsukuba Science City. In general, the campus facilities looked clean and orderly, whereas the shopping, diner alleys immediately neighboring the Central University looked unpleasantly dirty and run-down.

2.B RESEARCH INTERACTION AT TOYOHASHI UNIVERSITY OF TECHNOLOGY (TUT): TOYOHASHI GIJUTSU KAGAKU DAIGAKU

HOST INSTITUTION 2

Toyohashi Technology City
Toyohashi University of Technology
Faculty of Engineering Technology
Department of Information & Electronic Signal Processing
1 - 1 Hibarigaoka, Tempaku-cho, Toyohashi-shi 440

HOST / COORDINATOR

Prof. Yasumitsu Miyazaki, Director
Phone Nos.
TUT: 81-532-47-0111, Ext. 578/576
Home: 81-52-823-0875

Junior Professors

Dr. Nobuo Goto, Assoc. Prof.
Dr. Mitsuo Yanaga, Assist. Prof.

Research Plans:

1. Application of numerical techniques to RCS analysis of vehicle subsections (windows/wheels/doors/fenders/etc.).
2. Development of RCS control of ground vehicles (cars, trucks, busses), for the optimization of shape/material design of vehicles in future applications of polarimetric MMW crash avoidance and traffic control radar systems.
3. Development of suitable laser optical model simulation of ground vehicle experiments as well as real-life real-time dynamic compact RCS measurement ranges for MMW RCS matrix metrology in applications of vehicle traffic control.

Research Lectures:

Electromagnetic Inverse Problems
Inverse Methods in Radar Target Imaging
High Resolution Polarimetric Radar Target Imaging

Collaboration with Staff and Students

During my stay at Toyonashi lectures were in full session, and I really enjoyed interaction with the lively group of graduate students of Prof. Yasumitsu Miyazaki, well supervised by his junior research associates Drs. Nabuo Goto and Mitsuo Yamaga (see also Sect. 3.C). The experimental and computer research facilities of this young University of Technology are some of the best I have seen anywhere, and it was fascinating to observe their continuous use on all days of the week from very early morning hours to late night.

I was given the opportunity to visit many outstanding research laboratories of Prof. Y. Miyazaki's colleagues, and the one of Prof. Dr. Shiro Usui in Physiological Electronics impressed me in particular due to its wide scope covering advanced parallel-processing computer concepts and various aspects of neurophysiological electronics which he carried out in close collaboration with the Institutes of Biological & Physiological Sciences at Okazaki.

In summary, every minute of my stay on the campus was used for scientific discussions and interactions.

Research Publications

1. W.-M. Boerner: Fundamentals of Radar Polarimetry, A State-of-the-Art Review (invited) IEEE APS Tokyo Section to be published in the Technical Report section of the Institute of Electronics & Communications Engineering of Japan, attached.
2. Y. Miyazaki, W.-M. Boerner, M. Yamaga, N. Sato: Development of Numerical Methods for the Optimal Design of Polarimetric (Scattering Matrix) RCS Control of Vehicular Objects, to be published in IEEE Trans. Antenna and Propagation, by 1988.
3. M. Yamaga, N. Goto, W.-M. Boerner, Y. Miyazaki: Modeling, Simulation and Experimental Verification of the Concept of Polarimetric (Scattering Matrix) RCS Adaptive Control for Ground Vehicles, to be published in IEEE Trans. on Vehicular Technology.

Interaction with Neighboring Industrial Centers

In order to advance MMW traffic flow/hazard control radar technology, close interaction with neighboring Automotive/Electronic Research Centers have been initiated.

- a) Toyota Central Research Laboratory
R&D Engineering Center/Electronics Group
Nagakute, Aichi-ken 480-11
Car Radar Division: Mr. Teruo Yamanaka
Dr. Jun-ichi Kawamoto, Director
Mr. Kunitoshi Nishikawa

Topic: Assessment of Polarimetric MMW pulse compression radar techniques for traffic hazard control.

- b) Nissan Central Technology Center,
Nissan Motor Works / TTC Division, Automotive Radar Research
Laboratory, Yokosuka-shi;
Dr. Hirano Arai, Director

Topic: Advancement of polarimetric MMW traffic flow control radar technology.

- c) Suzuki Motor Co., Ltd.
Koshi (small cars/motorcycles) Plant
H520 Shirasuka, Kosai-shi, Shizuoka-ken
Robot Assembly Line Construction
Mr. Satoshi Nishida

Topic: Use of optical fibers and electro-opt. devices in electronic motor control.

- d) Headquarters, Suzuki Motor Co., Ltd.
Hamamatsu - Nishi
Box 1, Hamamatsu-shi, Shizuoka-ken 432-91
R&D Creative Center
Dr. S. Ishi, General Manager, R&D

Topic: International collaboration in the advancement of electro-combustion engines and of fiber optical electronic motor control: Suzuki-Isuzu (heavy trucks), GM (Chevrolet-trucks), Steyr/Daimler/Puch (Austria) BMW.

- e) Honda Electronic Co.
Ultrasonic/Electro-acoustic Sounding
Toyohashi-shi, Aichi-ken
Dr. Hitoshi Arai

Topic: Ultrasonic diffraction tomography and in ultrasonic microscope AMS-3400.

- f) Riken EMC, Inc.
Sekitori-cho, Mizuho-ku
Nagoya-shi 467
Electromagnetic Anechoic Chamber Systems Design
Mr. Ken-ichi Noda
Mr. Yosuke Tanaka

Topic: Multilayered absorbing material manufacture for multi-purpose anechoic chamber design.

- g) Brothers Industries, Inc.
(Yasuki Sewing Machine Co.)
Mizuho-ku, Nagoya-shi 467
Electronic Multi-Character Typewriter/Wordprocessor development
Mr. Takemi Yamamoto, Director R&D Division

Topic: Development of high-speed multi-character (Chinese/Japanese) script wordprocessor development.

Concluding Remarks on "Visits to Electronic Automotive R&D Engineering Centers"

It was most impressive to witness the rapid changes currently developing in the planning and research of novel automotive design concepts as a result of the recent advancements in electro-optics and electromagnetic imaging R&D and manufacture which include "Ceramic Motor Block Manufacture", "Integration of Fiber/-Electro-Optical electronic motor control", "Acousto-electric non-destructive diffraction tomographic material testing", etc. Contrary to what one reads, I found rather strong inter-industry exchange of information and close collaboration in international R&D.

In all of these R&D centers of these automotive/electronics manufacturing plants, independent R&D on special purpose robot design and implementation was carried out with tremendous backup of manpower and financial resources which I have not witnessed anywhere in Occidental/North American manufacturing industries. It seems that Japanese R&D&M in Automation and Robotics is outpacing that of all other industrial nations.

Interaction With Neighboring Academic & Government Research Institutions

The Toyohashi University of Technology and Science may be considered, in part, one of the many off-springs of its neighboring well established Nagoya Daigaku, one of the seven towering Imperial Universities, and there exist several other world-famed Research Institutes in this Chubu District such as the Nagoya Daigaku, Research Institute of Atmospherics in Toyokawa, and the various Institutes of Science (molecular, biological, physiological, etc.) at Okazaki, the ancient capitol city between Nagoya and Toyohashi. Certainly, I was very impressed with the enthusiasm, vigor and drive by researchers, scientists, engineers and support staff of the many research institutes I had visited within the Chubu District in such a short time period.

Here, a sincere word of thanks is due to Professor Yasumitsu Miyazaki, who not only is a real dynamo, whirl-wind and innovator of new ideas, but also a most talented organizer and coordinator, well-respected in all the industrial, academic and governmental laboratories we had visited together.

a) Nagoya University
Research Institute of Atmospherics
13 Honohara, 3-chome
Toyokawa-shi, Aichi-ken 442

a1) Atmospheric Electricity
Prof. Dr. Masumi Takagi
Dr. Akira Iwata

Topic: Use of polarimetric radar/ladar techniques in aerosol detection and characterization studies.

a2) VLF Radio Wave Studies
Dr. Masashi Hayakawa
Dr. Masanori Nishio

Topic: VLF-Space radio wave observations using similar wire-grid antennas to those used in Sugadaira, Matsushiro, Tokushima, Kagoshima, Toyokawa Aerosol Syowa Antarctic Station in conjunction with EXOS-D satellite experiments.

b) Okazaki National Research Institutes: Myodaiji, Okazaki-shi 444

These National Japanese Research Institutes in Okazaki are equalled only by a few such as the Max Planck Institutes of FR Germany, the Lebedev Institute of the USSR, the Princeton Institute of Advanced Studies of the USA. The excellence of the facilities, resources and especially the selected research staff are at the same level. All of us, the world over, will certainly become more familiar with the excellence of the pertinent research carried out at the National Research Institutes of Okazaki in Japan as time proceeds.

b-1) Institute for Physiological Sciences

As a result of the immense progress made in advancing biological/microbiological/biomolecular sciences, mankind is now able to approach electrophysiological research which will dominate applied electromagnetic-biological engineering and science for many years to come in order to understand the vital integrated electro-chemical functions of living tissue and organisms as a whole. This National Japanese Research Institute for Physiological Sciences certainly will take on a major leading position in this current global research effort.

Department of Information Physiology

Dr. Akimichi Kaneko

(close collaborator of Dr. Shiro Usui, Professor & Director, Physiological Electronics Laboratories, Dept. of Information & Computer Sciences, Toyohashi University of Technology)

Topic: Sensitivity of rods and cones on spectral intensities in color vision. Polarization dependence of mammal, fish, eal and insect eyes.

Department of Biological Control Systems

Dr. Hiroshi Irisawa

(cured my "hick-up" heart-misfiring problem due to overdoses of monosodium-glutamate (MSG) in preparing "Sushi" in one of the sushi resturants of Toyokawa).

Topic: Most inspiring and thought provoking overview on various novel discoveries of electro-chemical control mechanisms in biological organisms.

b-2) Institute for Molecular Science

Dr. Ei-ji Hirota, Prof. & Director

Extensive experimental studies on high resolution infrared analyses of molecular systems are carried out in one of the world's best equipped laboratory centers.

Chemical Dynamics Division

Dr. Kosuke Shobatake

Ultraviolet synchrotron orbital radiation facility for the study of molecule-molecule interaction.

Topic: Precise determenation of interaction times for atmospheric gaseous molecules.

The Campus of Toyohashi University of Technology

Similar to the campus of TUS, the campus of TUT on top of Tempaku/-Hibarigaoka is designed in an ultra-modern non-Japanese architecture, but in a

closed compact arrangement. Provided a more harmonious integration into its rural setting is achieved Gi-Ka-Dai may become a very desirable place to study. Again, a lot is to be desired similar to almost all Japanese University campuses about cleanliness, orderliness and environmental beauty! Yet, I wish to praise highly the well-selected shrub arrangements including many varied species of Tsu-tsu-ji (azaleas). Last but not the least, the surroundings of Toyohashi in all directions are very attractive; and very beautiful recreational national parks are close by which certainly adds to the overall location.

2.C HOST INSTITUTION 3: UEC UNIVERSITY OF ELECTRO-COMMUNICATIONS (DENKI TSUSHIN DAIGAKU) AND SUGADAIRA SPACE RADIO OBSERVATORY

- (1) Institute of Applied Electronics
1-5-1 Chofugaoka, Chofu-Shi, Tokyo 182
- (2) Sugadaira Space Radio Observatory

Host/Coordinator

Prof. Takeo Yoshino, Professor and Director
Phone Nos.

SRO: 81-268-74-2211

UEC: 81-424-83-2161, Ext. 3351

Home: 81-3-397-5577

Telefax: 81-424-84-6890 (UEC)

Telefax: 81-268-74-3467 (SRO)

Telex: Japan 2822 446 (UECJ)

Research Assistants

Mr. Ichiro Tomizawa
Mr. Takashi Shibata

Research Plans:

1. Thorough literature study on the fundamental geophysical / aeronomic effects leading to geo-electromagnetic precursor radiation centered about epicenters along the fault line just prior to seismic energy discharge (earthquake) discovered first by Gokhberg/Morgounov and Yoshino/Tomizawa.
2. Thorough analysis of the existing explanatory models discussed during the European Geophysical Society '84 Symposium Workshop W3: Magnetospheric Effects and Seismic Activity (organizers Lefeuvre/Gokhberg/Yoshino) Catholic University of Louvain, Leuven-la-Neuve, Belgium, 30 July-3 August 1984.
3. Identification of ELF/VLF frequency bands and windows open for setting up radiowave detection and epicenter radio-telemetry equipment. Coordination of VLF earthquake precursor emission detection with the International Geophysical Union, European Geophysical Union and URSI, Commission E (Electromagnetic Noise and Interference).
4. Mobilization of currently non-existing research activity in the U.S.A., especially at the U.S. Geophysical Survey, the Office of Naval Research, and the Army Research Office.
5. Establishment of global simultaneous detection experiments and R&D in equipment standardization and ground survey for zonal characteristics.

Research Lectures

Geo-electromagnetic Inverse Problems.

Geophysical Origins of EM Precursor Earthquake Radiation.

Development of Integrated EMPEQ radiation monitoring techniques.

Research Publications

1. W.-M. Boerner: An Overview on Current EM Precursor Earthquake Radiation Understanding (invited).
2. T. Yoshino, W.-M. Boerner, I. Tomizawa: On the optimal design of ELF/VLF sensor systems for optimal polarization control.
3. T. Yoshino/W.-M. Boerner, Workshop Lecture Notes on "Geophysical Origins of Electromagnetic Precursor Earthquake Radiation, Its Detection and Classification of the Associated Epicenters".

Collaboration with Staff and Students

During my stay, both at Denki Tsushin Daigaku in Chofu-shi and at the Sugadaira Space Radio Observatory, I sincerely enjoyed the interaction with Prof. Takeo Yoshino's highly motivated and dedicated research collaborators and graduate/undergraduate research assistants, who all had a very excellent background education in experimental and analytical electromagnetic wave engineering and aeronomy. Prof. Takeo Yoshino must be given high praise for his tremendous drive and skills in dealing not only with his staff but also with his peers and colleagues within UEC and all over Japan. His two doctoral candidates, Mr. Ichiro Tomizawa and Mr. Takashi Shibata, have been most accommodating throughout my stay and demonstrated great skill in the electronic design, construction, testing and operation of rather sophisticated ELF/VLF/HF wave probing transceiver systems, of micro-computer special purpose signal processors as well as of computer-assisted large-bulk data processing collected with ground-based, air/sea-borne and satellite-stationed ELF/VLF sounding equipment.

Indeed, it was a real pleasure to interact with these lively and talented, research-dedicated electronics students at either the home base in Chofu-shi or at the spacious SRO in Sugadaira so beautifully embedded in one of Japan's central mountain ranges. Whereas I found the research laboratories of Prof. Takeo Yoshino both at Chofu-Shi and at Sugadaira to be in hospitable and clean conditions, I dare to state here that the general conditions of orderliness and cleanliness of the UEC-Campus plus surroundings leave a lot to be desired. Thus, I hope that in my Phase II Report, I will not have to state that the UEC Campus facilities are among the dirtiest I have seen anywhere. I consider this topic of campus environmental conditions of great importance and will therefore devote a special section to this Japanese problem in Chapter IV of this Phase I Report.

The many inspiring hours in the company with Prof. Takeo Yoshino who introduced me, like no one else before, to so many different aspects of Japanese basic, secondary and higher learning, academic, governmental and industrial research institutions alike, will remain one of my greatest memories of life. The debt I owe Prof. Takeo Yoshino cannot be repaid, however, I will do my best to assist, wherever and whenever I will be able to, in his worthwhile research efforts which truly stand alone on a very high platform.

Before concluding, I would like to add here that I also enjoyed many discussions with Professor Tsutomu Suzuki and his able collaborators and students on advancing subsurface pulse compression radar technology. We also visited the Institute of Laser Science, one of the finest of its kind anywhere, where Professor Hiroshi Takuma is laboring with his large research staff on various aspects of high energy eximer lasers.

Interaction with Neighboring Research Institutes of the Kanto District

The location and especially guest house facilities, of the Campus of Denki Tsushin Daigaku at Chofu-shi, removed from the center core of Tokyo, were ideal for engaging in extensive and thorough interactions with neighboring academic, governmental and industrial research institutes as well as R&D Engineering Centers within the Kanto District. Whereas during the morning hours, we were occupied with teaching and research matters, during most afternoons we visited some of the great number of most outstanding R&D&M facilities of the Kanto District which cannot easily be duplicated anywhere. In the following only some of the many places visited are listed.

Academic Research Institutes

Due to the limited period of available time, a careful selection had to be made which included:

- a) University of Tokyo (Tokyo Daigaku)
Earthquake Research Laboratory
Prof. Takeshi Yukutake

Topic: Methods of electromagnetic earthquake precursor detection -
assessment of the current state-of-the-art.

- b) Tokyo Kogyo Daigaku

- b1) Electronics Department
Prof. Naohisa Goto and Makoto Ando

Topics: Electromagnetic theory and its application to antennas and
propagation

- b2) Electro-Optics Department
Prof. Yasuharu Suematsu, Dean of El. Eng.
Prof. Yoshiyuki Naito, Foreign Acad. Affairs Rep.

Topics: (1) Establishment of Academic & Research Exchange Agreement between
Tokyo Kogyo Daigaku and UIC
(2) Coordination of US and Japanese Engineering Educational
Programs for Asian countries

- b3) Earthquake Prediction Research center
Prof. Tsuneji Rikitake

Topics: Assessment of current electro-telluric research in earthquake
prediction

- c) Tokyo National College of Technology
The President's Office
Dr. Toshio Sekiguchi, Prof. & President

Topic: Enrichment of engineering curricula to include more courses and
emphasis on environmental quality protection, improvement and
control: water quality, air quality, radiation quality (monitoring
and control), ecological quality, recreational resources quality
and health quality.

- d) Waseda University
Physics Department
Prof. Mikio Namiki

It was a real delight to meet again with Prof. Mikio Namiki the famed theoretical physicist, and to be introduced to the most beautiful University Gardens I have ever seen in Japan or elsewhere. Waseda is a real pearl within a sea of stormy clusters of houses, streets and urban city activities.

Topic: The foundations of living, learning and researching and how to improve on our earthly and spiritual sphere of existence.

Governmental Research Laboratories

Some of the most important National Japanese Research Laboratories are located in the Kanto District and particularly on the western periphery of Tokyo of which Prof. Takeo Yoshino introduced me to

- (a) Radio Research Laboratory (DENPA KENKYUSHO)
Ministry of Post & Telecommunications
4-2-1 Nukui - Kitamachi
Koganei-shi, Tokyo 184
Dr. Noboru Wakai, Director General

This National Japanese Research Center in Electromagnetic Wave Engineering has become one of the focal points of global research in terrestrial-satellite-space communications covering almost all relevant research disciplines. Like all of the other Japanese National Research Centers, it is well equipped and so are its specialized Research Centers such as the Kashima Space Research Center. The National Japanese RRL certainly has attained the high rank of research excellence on the level of the FR German FTZ, and the former BELL Research Laboratories of the USA. Because RRL is very close to the campus of Denki Tsushin Daigaku, next to the beautiful Jin-Dai Botanic Garden of metropolitan Tokyo, I was able to make repeated visits of my own and all of them turned out to be most inspiring scientific events of which I wish to recall the following:

- (a-1) Office of Radio Physics
Dr. Tomohiro Oguchi, Chief Scientist

Topic: Advancement of polarimetric diversity radar polarimetry

- (a-2) Remote Sensing Research
Dr. Hideyuki Inomata, Chief

Topic: Advancement of polarimetric SAR

- (a-3) Radio Wave Propagation & Remote Sensing
Dr. Ken-ichi Okamoto, Chief
Dr. Takeshi Manabe

Topic: Analysis of major scattering objects within propagation path in the m-to-sub-mm wavelength region

- (a-4) Special Applications Division
Dr. Nobuyoshi Fugono, Chief

- Topic 1: Optical/IR remote sensing and SIR-B/C shuttle imaging radar;
polarimetric weather satellite imaging radar
- Topic 2: VLBI Experiment (Kashima): GPS-satellite

(a-5) Atmospheric Radio Science

Dr. Kozo Takahashi, Chief
Dr. Yoshihisa Masuda

- Topic 1: Acoustic sounding experiment (MU-radar with Kyoto University)
- Topic 2: VLBI-experiment at Kashima Space Radar System - Collaboration
with Prof. Takeo Yoshino
- Topic 3: Sub-ocean earthquake precursor radiowave emission detection
studies

(a-6) Antenna Research Section

Dr. Tasuku Teshirogi

- Topic: Polarization adaptive antenna design and applications in imaging
radar systems

(b) Institute for Space & Aeronautical Sciences: ISAS

ISAS: University of Tokyo Campus, 4-6-1 Komaba, Meguro-Ku, Tokyo 153

ISAS - Sagamihara Campus: New Testing Facility
ISAS - Uchinoura Launch Facilities

Whereas, the National Aeronautical & Space Development Agency (of Japan: NASDA) with its main facilities in Tsukuba (NASDA, Space Center) and Tanegashima (Launch Facilities) are mainly involved in industrial applications as for example, the launching of communications satellites; ISAS was created to deal purely with scientific space & aeronautical exploration similar to the functions of DFVLR (German Aerospace Research Establishment: Deutsche Forschungs- und Versuchs - Anstalt für Luft- und Raumfahrt) but quite different from ESA and NASA. Thanks to Professor Kyohei Fujimoto, I was able to visit the NASDA Tsukuba Space Center repeatedly and thanks to the unselfish willingness of Prof. Takeo Yoshino, I was able to visit many of the excellent facilities of ISAS at Komaba, Sagamihara, Uchinoura (Kagoshima Space Center), and USUDA Deep Space Radio Observatory which provided me with one of the best possible introductions to the current Japanese state of HI-TECH Space Science & Technology.

For a country of the size and the population of Japan, the quality and the excellence of the facilities as well as its carefully selected research staff are not only impressive but mind-boggling because of the displayed discipline, organization and strict resources conservation, i.e., one certainly is given the encouraging feeling that at least somewhere every penny is thoughtfully expended for the proper purpose.

Here, I wish to take the opportunity and express my sincere thanks to all of my hosts, Profs. Kyohei Fujimoto, Yasumitsu Miyazaki and in particular Takeo Yoshino for opening so many doors for me. It is impossible to properly account for all of the many new inspiring contacts made, and only a very succinct summary is provided here at this time.

(b-1) ISAS - Komaba
Office of the Director General
Prof. Dr. Minoru Oda
Drs. Masayuki Itoh and Yasuto Imai

Topic: Extension of Radon Projection Tomography to vector diffraction tomography and its application to x-ray/radio astronomic imaging (extension of Bracewell's initial studies)

Remote Sensing Division
Dr. Haruto Hirasawa, Chief
Dr. Zen-ichi Yamamoto
Dr. Ko-ichiro Oyama

Topic: Advancement of ground truth assessment in polarimetric space SAR imaging applications

Inspection of Research Facilities
Various divisions of the analytic & computer data processing research divisions of ISAS-Komaba were visited which impressed me because of its wide international scope of research interaction.

(b-2) ISAS - Sagamihara (New Main Campus & Test Facilities)
After a site visit of the testing facilities for research satellites by Profs. Yoshino and Hayashi, I was permitted to participate as an observer at an Experimenter's Meeting for the launch preparations of satellites EXOS-D and ASTRO-C

Topic: Japanese Research Contributions to the Observations of the Halley Comet (NATURE, 1986 May 15 - Special Issue)

(b-3) ISAS - USUDA Deep Space Observatory
During the four visits of the UEC - Sugadaira Space Radio Observatory, Prof. Takeo Yoshino also introduced me to the superb facilities of the Nobeyama Radio Astronomical Observatory of the Japanese Universities Research Council (Tokyo, Nagoya, Kyoto, Tohoku, etc.) with its (both) various large size antenna array systems and the USUDA Deep Space (40m dish) Observatory. Of great interest was the establishment of the very long base line (VLBI) interferometer [Kashima (RRL), Nobeyama, USUDA (ISAS) → Sugadaira (UEC)] and Prof. Yoshino's current engagement in setting up an additional 18m dish antenna. Again, I could fill a book on all the worthwhile and important observations made and thus, I shall summarize with the finding that the integrated system of Japanese Space Research associations/institutes/etc. (RRL, ISAS, NASDA, Universities, etc.) have provided for us (the international scientific research community) an immense scientific facility for studying hitherto untouched problems of aeronomic and geophysical research on terrestrial tectonic plate motions. Such a facility can only be created in a country with the scientific, technological and administrative structure like Japan has developed with sincere determination over the past century. When interacting with the many scientists, engineers, technologists and administrators on all levels, I found a spirit of joyful dedication and also deserved pride in their national accomplishments. However, much more so did I find everywhere the desire to share their gained wisdom and expertise with the international research community for the steady improvement of terrestrial living conditions. Although I found the Japanese scientists and engineers to be a

little too egocentric, I did not discover greediness but rather a childlike desire of sharing with all of us what they had achieved over the past century. In my opinion, it is now up to the rest of the world to accept the offer and come to visit Japan and study more about their undoubtedly superior "way of life and achievement in profession".

Topics: Polarimetric radar imaging and its application in deep space observations within the km-to-mm wavelength region

(b-4) ISAS - Kagoshima Space Center

Uchinoura-cho, Kimotsuki-gun, Kagoshima-ken

Dr. Saneo Watari, Chief Manager and Director of Facility

During a scientific research visit of Kyushu Island together with Prof. Takeo Yoshino, which included some of the most impressive guided tours through the ancient Japanese prefecture of Kagoshima with visits to the famed Kanoya Naval Air Force Base and the Sakurajima Volcano Research Institute of Kyoto University (Hakamakoshi Observatory), we were given a complete one-day site-visit of ISAS - Rocket Launch Facilities. Especially impressive was the overall planning of the launch facilities, the coordination of rocket launch/tracking/re-entry radar facilities with that of NASDA Tanegashima Island to the south, and Kashima (RRL) and the ISAS-Sanriku Balloon Launching Site to the north which so vividly demonstrated how intelligently and carefully the Japanese scientific community is utilizing its geographical location on the north-southern chain of small islands spread almost over the entire northern Pacific Orient. Although the heavily used launch and data processing facilities will require extensive collaboration of additional resources for modernization, again like everywhere else, I was impressed by the dedication and resources conservation of the operative and scientific staff.

Topic: After-effect of various recent rocket/space vehicle launch disasters on the Japanese space research rocket launch activities
(answers: Japan will also most carefully readdress every aspect of safety/precision/management of its launch facilities and operations).

(b-5) ISAS - SANRIKU Balloon Center (Balloon Launching Facilities): SBC

One of my first research interactions with Prof. Takeo Yoshiro involved the launching of relatively large research balloons for the monitoring of electric a.c. power line harmonics radiation of the 50/60 Hz fundamental frequency. In coordination with Prof. Yoshino's research on measuring such radiation not only over and across the Japanese islands but also laterally toward the Pacific and Japanese seas, a simple but quite effective system of controlling the azimuth of a payload gondola has been developed. Making use of high altitude stratospheric and low mesospheric winds flowing in different directions the boomerang operation was developed, where the lower currents (15 Km) during the summer weather are westerlies and the higher ones (30 Km) are easterlies. Such a boomerang method was also applied in our Canadian NSERC CCSS-Gimli Balloon Launch Facilities studies of 1978 to 1982.

Topic: Development of Polarimetric (direction finding) ELF/VLF measurement techniques for the detection of earthquake pressure radiation, etc.

- (c) Japan National Institute of Polar Research (NIPR)
9-10 Kaga, 1-Chome
Itabashi-ku, Tokyo 173
Dr. Ryo-ichi Fujii, Magnetospheric Physics.

The very impressive modern research and guesthouse facilities of NIPR are packed away in the quiet northern suburb of Itabashi-ku and definitely justified a visit due to the various ongoing research in meteorology, glaciology and aeronomy for which polarimetric radar imaging methods will become one of the essential tools in a more precise ground truth description of dynamic hydrometeor processes. Again, my sincere thanks are being extended to Prof. Takeo Yoshino and Dr. Ryo-ichi Fujii and their colleagues Drs. Takashi Yamanouchi, Hiroshi Kanzawa, Makoto Wada and Shuji Aoki for introducing me into their interesting polar research engagements.

Especially, I was introduced to the conjugate magnetic observation interaction of the Japanese Antarctic Research Facilities at Syowa, Mizuho and Molodezhnaya with those of the University of Iceland, Science Institute in Reykjavik in the vicinity of Husafell, Isafjodur, and Husavik which I was to visit later on in September 1986.

- Topic 1: Application of Polarimetric Radar Technology to Radar Meteorology
Topic 2: Discrimination of ELF/VLF/LF electromagnetic radiation signatures generated by man-made, by solar-terrestrial interaction, geotelleric and geo-tectonic sources and its relevance to the early detection and telemetry of earthquake precursor electromagnetic radiation epicenter sources

(d) Japan Meteorological Agency, Seismology Observatories

Although a visit to the Headquarters at Tokyo was planned, due to scheduling difficulties Prof. Takeo Yoshino was able to arrange for other visits at the Matsushiro Seismological Observatory as well as at the Yatsugatake Geomagnetic Observatory, Electromagnetic Earthquake Precursor Observing Station during one of our visits to the UEC Sugadaira Space Radio Observatory.

- (d-1) Matsushiro, Seismological Observatory
Japan Meteorological Agency
(member of ASRO Association of Seismic Research Observatories)
Matsushiro, Nagano-ken
Mr. Taizo Akiyama, Manager & Director

Hidden in one of the side valleys of the mighty river Shinano-Gawa near the capital city Nagano of Nagano prefecture - one of the world's most active seismic activity zones - lies the Matsushiro seismic observatory in a deep mine shaft (used as a shelter by the Imperial Family during WW-II) which for any scientist, whether seismologist or not, is one of the most impressive scientific observatories in size, extension and multitude of scientific permanent as well as modular testbed instrumentation facilities. In order to obtain a basis for comparison Prof. Takeo Yoshino also arranged for us to inspect the nearby much smaller standard

Hokushin Micro-Seismology
Research Observatory, Tokyo University
Earthquake Research Laboratory
and
Yatsugatake Geomagnetic Observatory
Electromagnetic Precursor Observatory, Tokyo University
Earthquake Research Institute
Mr. Shigeru Koyama, Chief

It was again most interesting to note that several interactive/interdigitizing Japanese Research efforts in seismology/geo-electromagnetics exist and are currently developing and expanding rapidly to include such novel methods as telluric current earthquake precursor detection (Prof. Takeshi Yukutake, University of Tokyo, Seismology Dept., Earthquake Research Laboratory), geo-electric current anomaly observations (Prof. Tsuneji Rikitake, Tokyo Inst. of Technology, Earthquake Disaster Prevention Research) and EM ELF/VLF earthquake precursor radiation detection (Prof. Takeo Yoshino, UEC). Certainly, the Japanese scientific and engineering R&D community has and is currently contributing most impressively to the establishment of this new and important scientific discipline of "geo-electromagnetic seismology" which may provide in the not-to-distant future more reliable methods of early advance-detection of earthquake epicenter allocation, etc.

Here, I wish to take the opportunity to express my sincere admiration about the extraordinarily wide research scope, breadth/width but also depth of execution and vision of aeronomic and geo-electromagnetic seismic terrestrial/global science carried out and pursued with such dedication and love by Professor Takeo Yoshino who has a hand in so many diverse aspects of pure and applied research. My sincere thanks for letting me share into so many valuable hours of his work-laden research are herewith sincerely acknowledged.

Industrial Research & Development Engineering Centers

The Kanto District contains one of the world's densest collections of HI-TECH Electronics Research & Development Engineering Centers and manufacturing facilities of which I was fortunate to be invited for presentations of Special Lectures, Research Short Courses and Panel Discussions at many occasions during the past fifteen years. A special note of thanks goes to Profs. Toshio Sekiguchi and Takeo Yoshino as well as their former students including Prof. Kyohei Fujimoto, Drs. Ken-ichi Kagoshima, Takao Namiki as well as Dr. Kiyoshi Nagai who opened the doors of many advanced concepts R&D centers which are not commonly visited by National and foreign "outsiders". In order to round off my overall experiences, here some of the many visits are being summarized.

- (a) The Furukawa Electric Company
Research & Development Division
6-1 Marunouchi, 2-Chome
Chiyoda-ku, Tokyo 100
Dr. Hidesaburo Nakano, Director & Chief of Engineering
Mr. Masami Iwasaki, Deputy General Manager
CTM Development, R&D Division
Mr. Takao Namiki, Deputy Manager
Fibre Optics, R&D Division

My first real longlasting contacts with the Japanese Electronics Industry resulted from my interaction with Mr. Takao Namiki, former student of Profs. Toshio Sekiguchi and Yasuharu Suematsu and with Mr. Masami Iwasaki dating back to the International Microwave Power Conference, Edmonton, Alberta Canada (1969), after which both visited the University of Manitoba, Winnipeg, Canada, where R&D in high tension electric powerline transmission as well as microwave power heating was carried out. During almost every visit to the Kanto District our previous contacts were re-established and expanded including R&D on high speed monorail mass transit, electro-optical and fiber-optics integrated circuitry. As a result of these long lasting friendships, I was able to meet and interact with various engineers and scientists of the Furukawa Electric Company as well as of its international sister company, Fujitsu Electric Company, during their visits to Northern America, Europe and Austral-Asia.

With great delight, I am recalling my various visits of 1970/71, 1978 and 1986 to the Chiba Works of the Furukawa Electric Company, which provided the continuity in assessing the true progress made over the years by the Japanese industrial R&D.

My recent visit of June 1986 to the Electro-Optical Fibre Cable Manufacturing Division of the Furukawa Chiba works clearly demonstrated to me how with dedication and persistence in the combined university-industrial advancement of research development world leadership is attained; here in the manufacture of graded-index optical fibres.

Topic: Advancement of fibre-optic integrated electronic signal/image processing with application to polarization radar (front-end) systems design

(b) Toshiba, R&D Center
Komukai, Toshiba-cho 1
Saiwa-ku, Kawasaki-shi 210
Dr. Kiyoshi Nagai, Director & Chief Scientist

Thanks to the continuing interaction with Dr. Kiyoshi Nagai, co-organizer of the International Symposia on Antennas & Propagation, Japan in 1971 and 1978, I was also able to monitor the dramatic expansion taking place more recently also under the directorship of Dr. Nagai, in applied electromagnetics, radar signal and image processing. Due to this long term interaction I was also able to witness the strong electronics research interaction among Toshiba, SIEMENS (FRG), PHILIPS (NL) and General Electric (USA).

Radar Electronics Division

Mr. Tasuku Morooka (former student of Toheo Yoshino)
Dr. Takeo Fukuda, Manager, Electronics Equipment Lab.
Dr. Yoshihiko Mikuni

Topic: Advancement of polarimetric radar research and its applications

(c) Mitsubishi Electric Corporation
Ofuna/Kamakura Works
325 Kamimachi-ya
Kamakura-shi, Kanagawa-ken 247
Ofuna R&D: Dr. Take-ichi Sato
Kamakura R&D: Dr. Takashi Katagi

My visit to the Mitsubishi R&D centers in 1986, the third since 1971/1978, was directed mainly toward communications satellite electronics development in coordination with that carried out at NASDA and ISAS as well as with

Dr. Yoji Furuhashi, Director
Optical & Radio Sciences R&D
Advanced Telecommunications Research Institute (ATR International)
Twin 21 MID Tower, 2-1-61, Shiomi
Higashi-ku, Osaka 540

with whom we carried out very timely discussions regarding the concepts for planning a new Science & Technology City in the Kyoto-Nara-Osaka triangle similar to establishing the Tsukuba Science City and the Toyohashi Technology City. During the various discussions on this topic, the importance of integrating a stronger foreign wing (i.e., engagement by foreign universities and industry) was stressed and re-emphasized.

Again, at Mitsubishi, similar to visits of other Japanese industrial R&D centers, it must be observed how drastically inter-factory environmental protection measures have been advanced during the past fifteen years. Thus, next to leadership in Electronic Devices R&D&M (manufacture), we are currently witnessing how the Japanese industry is carrying out a major brainstorm on how to best tackle the complicated problem of maintaining and improving on environmental quality. My personal guess is that Japan within a very short span of time (say ten years) will become the cleanest and most purified industrial nation as regards environmental control. In summary, it was a pleasure to visit the manufacturing and R&D facilities not only of Toshiba but in particular of Mitsubishi in one of the previously most polluted corners of the universe.

Topic: Advancement in the design of monolithic polarimetric phased array antenna system design concepts

(d) NTT - Nippon Telegraph & Telephone Corporation

(d-1) NTT Radio Communications Laboratory

1-2356 Taki, Yokosuka-shi
Kanagawa-ken 238-03

(d-2) NTT Basic Research Laboratory

9-11 Midori-machi, 3 chome
Musashino-shi, Tokyo 180

YOKOSUKA

Dr. Eng. Shuichi Shindo, Chief
Dr. Eng. Makoto Yoshikawa
Dr. Ken-ichi Kagoshima
Dr. Yuji Nagashima

MUSASHINO

Dr. Isao Masuda, Chief
Dr. Takunori Mashiko
Dr. Noriyoshi Osumi
Dr. Kei-ichi Ueno

Together with Prof. Takeo Yoshino, I was given the opportunity to visit for the first time both the NTT Radio Communications Lab. at Yokosuka by invitation of Dr. Ken-ichi Kagoshima, the former student of Prof. Toshio Sekiguchi, and by Dr. Kei-ichi Ueno, the student of Prof. Takeo Yoshino. In both cases electromagnetic vector wave propagation research was discussed placing emphasis on recent advances in polarimetric radar metrology.

Topic (Yokosuka): Polarimetric rain forward/backward scattering analyses
(Dr. Makoto Yoshikawa)

Topic (Musashino): Vector diffraction tomography (Deep sounding using dual
polarization radio wave analyses)

(e) The Nippon Electric Corporation

NEC Space Development Division

4035 Ikebe-cho, Midori-ku

Yokohama 226

Mr. Hironori Hara, Dep. Manager General

Mr. Takeshi Orii, Eng. Manager

Dr. Hideo Ono, Chief Engineer, Space Systems

Dr. Hiromu Kashihara, Chief Engineer, Electro-Optics

Mr. Katsutoshi Nakada, Aerospace Engineer

To visit the NEC Space Development Division at Yokohama, prepared and arranged so masterfully by Prof. Takeo Yoshino, was certainly one of the top ranking of so many outstanding visits to Japanese R&D Engineering Centers. It only takes a short stroll through these most perfected R&D&M facilities to recognize that NEC must rank among the "ICHI-YAMAS" of international HI-TECH industries. I was given a most impressive succinct review of the overall but also specific-relevant-to-my-interest R&D reviews and selected guided tours through their world renowned electro-optic fibre integrated supra-high speed signal/image processing device manufacture/packaging division.

Instead of visiting the

NEC Fuchu Plant

Guidance & Electro-Optics Division

1-10 Musashino-cho, Fuchu-shi, Tokyo 183

near UEC - Chofu-shi, Dr. Katsutoshi Nakada provided an overview of recent R&D&M advances as well as application of the first "Non-von-Neumann High-Speed (circular buss) Computer: NEDIPS (NEC Data Image Processing-Computer System) so that his colleagues of the Yokohama Plant all could partake in an interesting, thought provoking discussion on the design of electro-optic fibre optic-integrated monolithic phased-array antenna and polarimetric SAR systems design with near-to-real-time vector signal/matrix image processing using future versions of NEDIPS.

- Topics: (1) Polarimetric radar front-end systems design
(2) Dual polarization adaptive real aperture radar imaging
(3) Monolithic electro-optic phased-array dual polarization antenna systems

(f) Visits Planned to Other Industrial R&D Engineering Centers

Due to the acute time-scheduling limitations, visits planned during Phase I had to be postponed to the Phase II visit which will include visits to the Japan Radio Corporation, Fuchu-shi; the NISSAN Research and Development Center, Yokosuka; the HITACHI R&D Center, Kokubunji-shi; the Furukawa R&D Center, Shinagawa-ku; and the Matsushita R&D Center in Fujisawa-shi.

In summary, my visits to the industrial R&D centers within the Kanto District to me had become such a memorable chain of important events mainly due

to the many connections of Profs. Takeo Yoshino and Toshio Sekiguchi, whom I wish to thank once more including all of their former students and colleagues.

Foreign Research Offices

As a national and citizen of the United States of America, a former citizen of Canada, the Federal Republic of Germany (West), and of Papua New Guinea (PNG), Australia, I consider it my true responsibility to maintain contacts with the scientific divisions of my past countries of citizenship and particularly of the USA, and for completeness sake, here I am listing the Far East Branch Offices with whom I was in continual contact:

- (a) The Embassy of the United States of America,
Science and Technology Division
10-5, Akasaka, 1-chome
Minato-ku, Tokyo 106
Attn: Dr. Richard Getzinger, Director
Dr. Paul Di Angelo
- (b) The U.S. Department of the Navy
Offices of Naval Research/Technology
Science Liaison Office: Far East Branch
Akasaka Press Center
7-23-17 Roppongi
Minato-ku, Tokyo 106
Attn: Dr. George B. Wright, Director
- (c) U.S. Air Force Office of Scientific Research - Far East Branch
ibid
Attn: Dr. James W. Wolfe, Chief Electronics Division
Dr. Soon Park, Chief Technology Division
- (d) U.S. Army, Army Research Office - Far East Branch
ibid
Attn: New Appointment

Although I found out to my surprise and certainly also distress that great apprehension exists among Japanese researchers of all section, industrial, governmental and particularly academic R&D institutes toward having any relations with foreign R&D Liaison Offices, and especially toward the US-DoD Far East Branch Offices, I made it one of my special assignments to break down fences created by misunderstanding. Namely, during my visits to the Akasaka Press Center in Roppongi, I did not experience or witness any type of hostile actions toward Japan. On the contrary, I found that a rather openminded, friendly atmosphere prevailed under the able directorship of Dr. George B. Wright and, therefore, I wish to invite my Japanese scientific friends and colleagues of academia, government and industry to reassess their positions and to contribute toward the

Scientific Bulletin
Department of the Navy
Office of Naval Research, Far-East
Department of the Air Force
Air Force Office of Scientific Research, Far-East
ISSN: 0217-7077
ONR Liaison Office, Far East
APO San Francisco, CA 96503-0007

with executive summaries and current updates of their R&D&M activities for the improvement of international relations and particularly for strengthening the ties between the United States Of America and Japan.

(c) Embassy of the Federal Republic of Germany
5-10, Minami Azabu 4-chome
Minato-ku, Tokyo 106
Science & Technology Division

(d) The Canadian Embassy
3-38, Akasaka, 7-chome
Minato-ku, Tokyo 106
Science & Industry Division

2.D RESEARCH INTERACTION WITH THE UNIVERSITIES (NPU, NWTCEI, NW
JIAO-TONG) OF XIAN, SHAANXI PROVINCE, P.R. CHINA

HOST INSTITUTION 4.

(D1) Northwestern Polytechnical University Faculty of Electrical and
Electronics Engineering, Applied Physics and Wave-Propagation Institute
Xian, Shaanxi Province, P.R. China
(88) 29-51491

Host/Coordinator

Prof. Dr. Liu, Yuang-Yong, Vice President
Prof. Chen, Guo-Ruy, Head, Electrical Engineering
Prof. Zhang, De-Chang, Head, Applied Math.
Prof. Lin, Shi-Ming, Coordinator

Collaborating Institutes/Universities in Xian

(D2) Northwestern Telecommunications Engineering Institute (NWTCEI)
Department of Electromagnetic Engineering
Xian, Shaanxi Province
(88) 29-53291
Attn: Prof. Chen, Huai-Chen, Vice-President
Prof. Bohan, Qiang, Director, Institute of Scientific Research
Prof. Wang, Mao-Guang, Director, Electrical Engineering
Prof. Wang, Yi-Ping, Co-director, Electrical Engineering
Prof. Mao, Yu-Kuan, Associate Director, Electrical Engineering
Dr. GE, Dao-Bin, Associate Professor

(D3) Xian (NW) Jiao-Tong University
Department of Information and Control Engineering
Institute of Radio Engineering and Radar
Xian, Shaanxi Province, P.R. China (88) 29-32911
Attn: Prof. Shi, Wei-Xiang, President
Prof. Jiang Deming, Vice President
Dr. Wang, Wen-Bing, Prof. & Director
Dr. Yang, Ru-Gui, Prof. & Department Head

(D4) Xian Radio & Radar Technology Institute
Radar Antenna & Signal Processing Division
Xian, Shaanxi Province, P.R. China
Attn: Dr. Chen, Cao, Professor

(D5) China Academy of Electronic Technology
NW China Research Institute of Electronic Equipment
Radar Signal Processing Division
Math. Methods Department
Mei-Xian, Shaanxi Province, P.R. China
Attn: Dr. Gao, Xiao-Ju, Prof. & Director
Dr. Yang, Cheng-Lin, Prof. & Department Head

RESEARCH PLANS

- (1) Development of High-Resolution Radar Target Description using Electromagnetic Inverse Scattering Techniques
- (2) Application and Extension of Kennaugh's Radar Target Characteristic Theories to High Resolution Polarimetric Radar Signal Analysis
- (3) Advancements of the fundamental theories of polarization radar technology
- (4) Advancement of Electromagnetic Inverse Theories and Techniques applicable to Radar Remote Sensing and Subsurface Radar Sounding

Research Lectures

- A. Electromagnetic Inverse Problem
- B. Kennaugh's Physical Optics Radar Target Ramp Response Method
- C. Extension of Scalar to Tensorial Diffraction Tomography
- D. Basic Radar Polarimetry and its Extensions
- E. Recent Advances in High Resolution Polarimetric Signature Analysis
- F. The Electromagnetic Inverse Problem Applied to High Resolution Radar Signature Analysis

Collaboration with Staff and Students

During my two recent CAST award fellowship visits to Xian of September 1985 and July 1986, I have provided in total eight days of solid lectures and developed the basis for future active research collaboration and exchange of mature and young scholars in the newly emerging science of "Inverse problems in Electromagnetic Imaging". During the second visit I explored the possibilities of expanding on already existing research activities and collaboration developed during the Visiting Scholar Award tenure of Prof. Lin, Shi-Ming to UIC-EECS/CL of 1985 November to 1986 May, and with Assoc. Prof. Ge, Dao-Bing during his repeated visits to the USA and Europe.

During my July 1986 research visit I had presented an Advanced Research Short Course Lecture series which was attended by about forty-five (45) to sixty (60) radar research experts from all over China including the following out-of town radar experts:

1. Nanjing Institute of Technology, Radio Department
Prof. Wu, Shu-Mei
Prof. Zhang, Wen-Xiao
Prof. Chen, Xiao-An
2. Peking University, Radio Electronics
Prof. Miao, Jan-Gang
Dr. Liu, Yong-Hua

3. Dalian Marine College, Radio Engineering
Prof. Li, Zhi-Xin
4. University of Science & Technology of China, Beijing
Dr. Sun, Huai-Ye
5. Wuhan University, Space Physics
Prof. Zhou, Cheng-Xi
Dr. Zou, Li
6. East China Institute of Technology, Electr. Engr.
Dr. Wang, Gao-Feng
7. Hefei Polytechnical University
Prof. Yang, Jiang-Yin
8. Beijing Institute of Technology
Prof. Yang, Yan-Mei
Prof. Li, Shi-Zhi

It was then decided after this short course that our research collaboration be extended to include my Japanese host professors and that in a first step Prof. Kyohei Fujimoto be invited to provide a lecture short course in his field of expertise during the 1987/88 academic sessions. During my entire stay in Xian, I enjoyed the guidance and hostship of the post-graduate students of NPU NWTCEI, including:

Miss Tang, Xiao-Gi, Mr. Li Ning,
Mr. Yuan Hao, Mr. Ma Gou-Zhang,
Mr. Ding Jan, Mr. Guo Cheng-Jiang,
Mr. Chang Yu-Feng and Mr. See Cheo-Wei.

We also attended together a classic chinese opera, various literary and musical presentations, visits to the outstanding museums within and around the old city of Xian as well as leisurely hikes along the rebuilt massive road on top of the ancient city wall.

Publications

W-M. Boerner (invited), Inverse Methods in Electromagnetic Scattering,
(translated in Chinese by Prof. Lin, Shi-Ming), China IECE Trans A&P Journal, in print (Spring 1987)

W-M. Boerner (invited), Recent Advances in Radar Polarimetry-A succinct Review
(translated by Prof. Lin, Shi-Ming), China IECE Trans. A&P Journal, Fall 1987

Lin, Shi-Ming and W-M. Boerner, Some Properties of the Kennaugh Ramp Response and the First Order Correction for the Bistatic Case— A Frequency Domain Analysis, Submitted to Radio Sci., Oct. 1986

Lin, Shi-Ming and W-M. Boerner, Some Properties of the Kennaugh Ramp Response and the First Order Correction for the Bistatic Case— A Time Domain Analysis, accepted by China IECE Trans. A&P Journal, Fall 1987.

Lin, Shi-Ming and W-M. Boerner, On the Discrete Radon Transform in three Dimensions, in preparation, JOSA, 1987/88.

Lin, Shi-Ming and W-M. Boerner, On the radar scattering matrix and the ramp response for the dielectric object case, in preparation, Radio Science, 1987/88

Interaction with Neighboring Academic Governmental and Industrial Research Institutes

The rapidly expanding metropolitan area of Xian has been chosen to become one of about five major radio/radar electronics and space electro-optics Research & Development & Manufacturing centers of PR China under the auspices of the PRC Ministry of Aviation & Aerospace Industry. Therefore, most of the not easily overseeable academic, governmental & industrial R&D institutes and centers, and there is a great many of them in and around Xian, are geared toward radar electronics and electro-optics, and in turns, the academic teaching and research activities are to provide background education in these areas of HI-TECH specialization.

During my first two stays of very limited durations I was given the opportunity to visit mainly academic (NPU, NW Jiao-Tong, NWTCEI, NW Mining Institute), a few governmental Research Laboratories (Xian Radio & Radar Laboratory Institute, China Academy of Electronic Technology/Radar Signal Processing: Mei-Xian) and only one industrial laboratory (Xian Optics industries). Because the visits were rather succinct no detailed reports are provided here.

However, my short course lecture series was so arranged that one day of presentation out of the total of eight days was each presented at NW Jiao-Tong and at NWTCEI.

During the relaxing after-evening lecture gatherings, there existed ample opportunity for strong research interaction with research experts from Xian and elsewhere. Especially it was interesting to note that young Chinese Scholars prefer a research stay in Western Europe over North America and Japan. Whereas most Chinese engineering scientists are rather fluent in English and to some lower degree in French, German and Russian, there existed little linguistic capabilities of the Japanese language. However, almost all engineering scientists expressed the desire that after a first prolonged visiting scholarship tenure in the Occident and/or North America, they would very strongly like to also spend at least one or two years in Japan. Essentially, they all agreed that it would be of greatest benefit to the Chinese engineering scientists if a triangular research interaction system Occident/North America—Japan/Korea/Taiwan—PR China could be developed over the nearer future.

Indeed, there existed all over a great longing for increased interaction with the outside world, expansion of the educational and academic institutions in China which have suffered most severely during the past cultural revolution.

Here, we need to emphasize that in most smaller rural communities there do not exist formal school instructions, that illiteracy in PR China is rampant and that "true self-education" without "formal school education" is being widely practiced. Thus, it is not surprising to find that institutes of higher learning (technical colleges) provide entrance examinations for "self-educated applicants"! These indeed are very interesting developments which require sincere attention because new avenues of by-passing the strict castigation of a formal school system may be developed which allow "late developers" to obtain a fairer chance of receiving a good university education. Certainly, this topic should also be great concern to Japanese educators as a whole.

III RESEARCH TRAVEL, LECTURE PRESENTATIONS, VISITATIONS & ATTENDANCE OF CULTURAL ACTIVITIES

3.0 Synopsis

In this chapter the chronological listing of research travel activities, visitations and academic, governmental and industrial institutions, foreign research/science liaison offices as well as of cultural events are provided together with summaries of observations made during travel and discussions which I consider relevant. Due to the fact that I had been provided with the opportunity to interact on so many different levels in so many varied domains of the Japanese sphere of life, it is impossible to draw concise conclusions, and therefore a telegram-style of succinct listing of events is adopted.

3.1 CHRONOLOGICAL LISTING OF SPECIFIC RESEARCH/CULTURAL VISITATIONS BY DATE/LOCATION/CONTACT

3.1A Visitation of Academic Institutions

"Optical Inverse Scattering", University of Electro-Communications, Institute for Laser Science (Prof. Hiroshi Takuma), April 12, 1986.

"Radar Polarimetry", Tokyo Institute of Technology, Tokyo, April 16, 1986.

"Inverse Problems in Geo-Electromagnetism (with T. Yoshino), Sugadaira Space Research Observatory, UEC, Sugadaira, Tokyo, April 19, 1986.

"Early Detection of Electromagnetic Earthquake Precursor Radiation (with T. Yoshino), Yatsugatake, Japan Earthquake Research Institute, Tokyo University, April 21, 1986.

"Electromagnetic Inverse Problems", Tsukuba University of Science, Tsukuba, April 25, 1986.

"Polarimetric Perception by Insects, Fish, Birds, Mammals and Man", Toyohashi University of Technology (Toyohashi Gijutsu Kagaku Daigaku), Department of Physiological Electronics, May 7, 1986.

"Interrelation of Geo-electromagnetic Earthquake Precursor Radiation and Atmospheric Optic Observatory", Nagoya University, Research Institute of Atmospherics, Toyokawa, May 8, 1986.

"The Electromagnetic Imaging Problem and the Detection of Buried Obstacles", Toyohashi University of Technology, Toyohashi, May 15, 1986.

"Electromagnetic Inverse Problems and High Resolution Radar Imaging", Kyoto University, Electromagnetics Department, Kyoto, May 16, 1986.

"The Electromagnetic Inverse Problem", Osaka University, Department of Electronic Communication Engineering, Osaka, May 19, 1986.

"Electromagnetic High Resolution Imaging", Osaka Denki Tsushin Daigaku, Osaka, May 20, 1986.

"The Electromagnetic Inverse Problem", Kyushu University, Fukuoka, invitation by the Japan Institute of Electronics & Communications Engineering, Annual

(Tokyo/Kyushu Chapter) Meeting, May 27, 1986.

"Radar Polarimetry", Denki Tsushin Daigaku, Department of Applied Electronics, Radar Laboratory, Chofu-shi, May 30, 1986.

"Electromagnetic Earthquake Precursor Sensing and Identification", Denki Tsushin Daigaku, Sugadaira Space Radio Observatory, May 31, 1986.

"The Electromagnetic Inverse Problem", Tohoku University, Electrical Engineering Department, Sendai, June 23, 1986.

"Radar Polarimetry", Iwate University, Electrical Engineering, Morioka, June 24, 1986.

"The Electromagnetic Inverse Problem", Hokkaido University, Electronic Engineering Department, Sapporo, June 25, 1986.

"Detection of EM Earthquake Precursor Radiation", Akita University, Geology Department, Akita, June 27, 1986.

"Electromagnetic Deep Sounding and Imaging", Niigata University, Electronic Engineering Department, Niigata, June 28, 1986.

"The Optical Inverse Scattering Problem", Tokyo Kogyo Daigaku, Opt. Electronics, O-Okayama, Meguro-ku, June 30, 1986.

"Research Short-Course Lectures on Inverse Methods in Electromagnetic Imaging", Institute of Applied Mathematics and Electromagnetic Wave Propagation, Northwestern Polytechnical University, Xi'an, Shaanxi, PR-China, July 3 to 10, 1986.

"Current State-of-the-Art in Sensing and Detection of EM Earthquake Precursor Radiation", Science Institute, University of Iceland, Reykjavik, Sept. 11-12, 1986.

"Collaborative Academic/Research Interaction Between the University of Iceland and the University of Illinois at Chicago, Faculty of Engineering, School of Engineering, University of Iceland, Reykjavik, Sept. 12, 1986.

3.1B Visitation of Governmental Institutions

"Electromagnetic Problems and Ocean Wave Imaging", invited lecture at the Institute of Applied Physics, Educational Media Center, University of Tsukuba, Japan, April 7, 1986.

"Polarimetric SAR Imaging", invited lecture at the NASDA, Electromagnetics Division, Tsukuba, Japan, April 9, 1986.

"The Electromagnetic Inverse Problem and Rain Scatter Analysis", invited lecture at the Japan Ministry of Posts & Telecommunications, Radio Research Laboratory, Koganei-shi, Tokyo, Japan, April 11/15/22, 1986.

"Electromagnetic Imaging of Underground/Sea/Ice Objects", invited lecture at the Japan National Institute of Polar Research, Itabashi-ku, Tokyo, June 16 (AM), 1986.

"Interpretation of Polarimetric SAR Imaging", invited lecture at ISAS-Komaba, Remote Sensing Division, Japan, June 16 (PM), 1986.

"Polarimetric Radar Meteorology", invited lecture at the Japan Meteorological Research Institute, Tsukuba, June 20 (AM), 1986.

"Detection of Electromagnetic Earthquake Precursor Radiation", invited lecture at the Japan National Center for Disease Prevention, Earthquake Prediction Division, Tsukuba, June 20 (PM), 1986.

"Polarimetric SAR Image Interpretation", invited lecture at the Ministry of Posts & Telecommunications, Radar Research Laboratory, Remote Sensing Division, Tokyo, July 1, 1986.

3.1C Visitation of Industrial Institutions

"The Electromagnetic Inverse Problem in High Resolution Radar Target Imaging", Toshiba RDE Center, Kawasaki, Tokyo, April 18, 1986.

"Radar Polarimetry and Satellite Remote Sensing", Mitsubishi (Kamakura/Ofuna works), Kamakura, April 18, 1986.

"Electromagnetic Inverse Problems", Nippon Telegraph & Telephone Co., Yokosuka, Electronics Communication Lab., April 23, 1986.

"Optical Inverse Problems and High Speed Opto-Electronic Signal Processing", The Furukawa Electric Co., Chiba, April 24, 1986.

"Optical and Millimeter-wave Precision Imaging Using Electromagnetic Inverse Methods", Suzuki Motor Co., Kosai Plant, Shizuoka, May 07, 1986.

"Polarization Perception by Insects, Fish, Eel, Birds, Mammals and Man", The Japan National Institute for Physiologic Electronic Sciences, Okazaki, May 9, 1986.

"Use of Millimeter-wave Radar in Traffic Control", Honda Electronics Research Center, Toyohashi, May 13 (AM), 1986.

"High Resolution m-to-mm-wave Imaging", Riken EM (Absorbers), Inc., Nagoya, May 13 (PM), 1986.

"The Electromagnetic Inverse Problem and High Resolution (Precision) Imaging in the m-to-sub-mm wavelength Region", Toyota Research Laboratory, Nagakute, Aichi, May 14 (AM), 1986.

"Applications of Electromagnetic Imaging Methods to Design of Millimeter Precision Robot Control in Auto-Motion", Brothers Industries, Mizuho-ku, Nagoya, May 14 (AM), 1986.

"Electromagnetic Imaging of Underground Obstacles", NCC Musashino Research Laboratory, Musashino, May 28, 1986.

"High Resolution Polarimetric Radar Imaging", Nippon Electric Company, NEL Space Development Division, Yokohama, May 29, 1986.

"High Resolution Radar/Ladar Imaging", Furukawa Electric Company, Opt. Fiber/Integrated Circuits Division, Chiba, June 17, 1986.

"Use of Millimeter-wave Radars in Traffic Flow Control", Hitachi Central Research Laboratories, Kokubunji, Tokyo, June 19, 1986.

3.2 MAJOR RESEARCH TRAVEL INCLUDING HOST INSTITUTION RESEARCH OBSERVATIONS & VISITS

In addition to the many one-day short site visits with lecture presentations, listed in Section 3.1, the various off-host-campus research travel is here summarized into four separate major research travels.

3.2A NORTHERN HONSHU/HOKKAIDO ISLAND TRAVEL

With the acquisition of a Seven (7) Day Japan Rail Travel Pass from JTB-Chicago Foreign Branch Office and the kind assistance of Prof. Kyohei Fujimoto, a One-week rail-round trip was planned and executed:

Tsukuba/Ueno - Sendai - Ichinoseki - Morioka - Aomori - Hakodate - Sapporo - Hakodate - Aomori - Hirosaki - Noshiro - Akita - Shibata - Niigata - Takazaki - Ueno/Shinjuku.

Although I had no trouble in traveling by myself, certainly it would have greatly facilitated my travel had JSPS made available a "National Visiting JSPS Scientist Passport" similar to the one made available for Rhodes Scholars or Alexander von Humboldt fellows (see attachment). I consider this one-week travel most essential for the overall accomplishment of my JSPS-fellow tenure program, as I will briefly summarize.

A.1 Visit of Cultural Sites & Nature Parks Around Tsukuba-Yama

Whenever I had spare time I enjoyed visiting the well-developing Tsukuba Botanic Garden after having been given the privilege to enter the gardens early in the morning long before official gate hours. Especially perfected is the Japanese Wild Flower and Shrub Section, where I saw various rare and in nature protected early spring flowers. It also was the senior curator, Dr. Tamotsu Hashimoto, who referred me to the three-volume encyclopedia on "Wild Flowers of Japan" by Yoshisuke Satake, Jisaburo Ohi, et al., of which the short field copy has been translated by the Smithsonian Institute, Washington, D.C./USA. During one of my Botanic Garden excursions I also got to know the veterinarian Dr. Masao Gotoh, his wife Yukie and children Michitaka and Sara with whom I had spent many hours in the nature parks surrounding Tsukuba-Yama, where the Tsu-Tsu-Ji (azalea) were in full blossom at the Tsu Gamma Ji shrine and the encroaching mountain botanic garden.

The Gotoh's also happened to be dedicated collectors of Chinese and Japanese ceramics, pottery, and chinaware and they introduced me to the Ceramics (Yaki-Mono) Dictionary (Jiten) on Japanese porcelain Kurihiko Shimonaka, Yaki-Mono-Jiten, Heibonsha, Ltd., 1984, ISBN-4-582-12901-3 (in Japanese) which I acquired at the Maruzen Book Store in Nihonbashi, Tokyo. A translation into English of this excellent encyclopedia is currently being prepared by the Smithsonian Institute, Washington, D.C. and it should become very handy for a collector of Japanese ceramics in that all local kilns of relevance are properly listed such as the famed Kasama-Yaki created on the northern foothills of Tsukuba-Yama and the more recent Mashiko-Yaki which developed from it.

Thus, I was very pleased when Prof. Kyohei Fujimoto, also a devoted amateur painter, offered to guide me around Tsukuba-Yama in order to visit the local kilns producing Kasama-Yaki, Mashiko-Yaki and various other types of ceramics developed from those. Later on, I was to visit the Kurita Museums both in Ashikaga and Nihonbashi-Hamacho, Chuo-ku, Tokyo, where a most pleasant collection of Imari-Yaki and Nabeshima-Yaki of Saga-ken, Kyushu Island are displayed.

Provided with these precious guided lecture tours on "Nippon-Yaki" and introduction to Japanese Wild Flowers and Shrubs, I was well prepared to leave for my North-Honshu/Hokkaido Shinkansen/Special Express train tour starting at Arakawa-Okii train station close to the TUS campus.

A.2 Visits of Sendai and Tohoku University

Dept. of Electrical Engineering

Aramaki Aoba

Sendai 980

Attn: Prof. Saburo Adachi

Dr. Toru Uno

Dr. Akihiko Ohashi

Dr. Sei-ichi Takeuchi

Prof. Saburo Adachi first guided me to the new Sendai/Miyagi-ken Museum complex which certainly is a very pleasant and delicate esthetic achievement in modern architecture providing a very informative historical essay of Hasekura Tsunenaga during the 17th century who was the first Japanese to visit renaissance Europe. Unfortunately, the tremendous efforts and good contacts made by the Japanese explorer Hasekura Tsunenaga were not used, and Japan instead withdrew into seclusion. Yet, from our most pleasant morning hike through the Buddhist Temple gardens where I enjoyed the early blossoms of iris, one certainly may conclude that it was not a wasted period but allowed Japan to contribute most extensively to terrestrial culture by further perfecting its own artistic style originating from Zen Buddhism. Here, it is worth mentioning that JSPS on behalf of the Japanese Ministry of Education should embark in generating and creating Japan's own world-wide chain of Institutes of Japanese Culture similar to the Goethe Institute of the Federal Republic of West-Germany. I would like to anticipate that Sendai like Kobe, Hakodate and Kogoshima, for example, could become guest cities to host such cultural institutions where we JSPS fellow guests may be hosted to past and current Japanese ways of life (see Chapter 4, Section 4.6).

It was my third visit to the EE Department of Tohoku University which definitely counts to be one of the leading Electrical & Electronics Engineering Sciences Institutes anywhere. I was very impressed by the research conducted under the supervision of Prof. Saburo Adachi who is engaged in various electromagnetic inverse scattering analyses.

- Topics: (1) Uniqueness of solution of inhomogeneous slab problem (Kruger, Ames Research Institute: Dr. Toru Uno)
- (2) Polarization correction of Kennan-Cosgriff ramp response identity (Dr. B.-Y. Foo/UIC - Dr. Akihiko Ohashi): Proc IEEE 53(8), pp. 1067/8, August 1965.
- (3) Polarimetric Radar Target Imaging (Dr. Sei-ichi Takeuchi - Dr. Alexander B. Kostinski)

A.3 Visit of Hiraizumi/Ichinoseki, Morioka and ferry to Hakodate

Instead of using the Special Express Tohoku Shinkansen Sendai-Aomori, I used the earlier means of the Limited Express Shinkansen with stop in Ichinoseki and used taxi to visit Hiraizumi and the beautiful Mitsu-ji Ayame Matsuri iris gardens containing all three major species of iris, the water iris Hana-Shobu, the dry iris Ayame, and the wetlands Kakitsu-Bata. Although it was a "mad" return-taxi rapid sightseeing tour, it has enticed me to return to Hiraizumi during Phase II in order to study those beautiful temples, shrines and parks with more leisure.

Because of a delay for catching the next rapid special express from Morioka to Aomori and the last ferry-boat with train connection in Hakodate to Sapporo, I had some spare time in Morioka which I used for another "mad" taxi-round trip including a site visit to the Iwate University in Morioka.

The Aomori-Hakodate ferry to Hokkaido Island was a most entertaining adventure regarding the interaction with the passengers. On the other hand, it was most depressing to witness the almost perfect environmental destruction of the Matsuwan Bay and Tsugaru-Kaikyo Strait (and later on the Uchiura-wan Bay along which the Hokkaido Line "expressed" for hours!). Certainly, there exists every reason for the Japanese People to clean up the environmental mess created before, during and after the blind WW II industrial expansion phase.

A.4 Visit of Sapporo and Hokkaido University

Dept. of Electrical Engineering

N-13, W-8 Kita-ku

Sapporo 060

Attn: Prof. Kiyohiko Itoh

Prof. Ichiro Fukai

Prof. Michio Suzuki

I enjoyed my second visit of 1986 to Sapporo, the Japanese Munich, just as much as I did during my first visit of 1978, and in every sense I find it a refreshing, pleasant city to live in. Prof. Kiyohiko Itoh first guided me through the classical Botanic Garden of Hokkaido University which was created at about the turn of the century. Hopefully, this precious garden will be able to sustain the pressures from modern downtown developers and remain forever where it is. Especially, I enjoyed the selected iris species of the type kakitsubata and ayame. After viewing the Botanic Garden and the beautiful downtown campus of Hokkaido University, Prof. Itoh introduced me to his colleagues and graduate research students who impressed me sincerely by their breadth and depth of knowledge.

Topics: (1) adaptive polarization switching techniques for microstrip antenna arrays,
(2) development of polarization-adaptive beam steering & scanning array antennas.

A.5 Visits of Hakodate, Aomori, Hirosaki, Noshiro, Akita, Shibata and Niigata.

On my travel back with the first morning Hokkaido Line Express to Hakodate I enjoyed a one-hour rapid taxi-round trip both in Hakodate and Aomori visiting famed historic sites. Especially, the historical city of Hakodate caught my special attention due to its beautiful surroundings.

The rapid express along the Uetsu-Line from Aomori via Hirosaki, Noshiro to Akita, where I stayed for one day, then continuing on via stop-over in Shibata to Niigata was one of my most memorable train rides among the very many I had enjoyed world-wide. The Uetsu-Line train travel along the Japan Sea Shore of the Tohoku District provides, may be, one of the last glimpses into pre-modern Japanese way of life, and this specific train travel is certainly most recommendable for anyone who wishes to learn more about Japan. Especially, I found Akita with the Oga-Hanto peninsula to the northwest picture-book-like "Japan", the way we learned about it in school. Again, due to severe time-limitations I hired a taxi for a four hour round-trip with English-speaking taxi driver which are indeed hard to come by in the northwestern corner of Honshu Island. I was fortunate to be able to enjoy the most beautiful Akita Botanic Garden where an extensive iris exhibit was in full bloom. Unfortunately, Prof. Noto of Akita University was not in town and there was also little time left to visit either the RRL-Observatory or the ISAS Rocket Research Facilities near Akita.

Upon the kind advice of the curator of Akita Botanic Garden, I then embarked for the next possible train to view another even more complete iris exhibit in the military city of Shibata before turning in for the night into the famed Italia-ken Hotel in Niigata. In Niigata I briefly toured by "rapid" taxi the old downtown and the new suburban campuses of the University of Niigata, but I had no time to visit the Electrical Engineering Department with Prof. Takeo Abe and Assoc. Prof. Masakazu Sengoku, whom I plan to visit more extensively during Phase II.

In order to partake in acoustic radar research experimentation at RRL-Koganei-shi, I could not stay longer in Niigata after attending the marriage of a long-time friend in the Tokiwa-kaikan Marriage Institute close to the WW II Veterans Memorial of Japan.

Leaving Sado-shima and Niigata behind, I returned to Ueno on the Joetsu Shinkansen, another most memorable train ride across the North Central Honshu mountain range through the most beautiful Niigata and Gumma prefectures. At the Takasaki train station I interrupted this very rapid ride and stopped over in Ashikaga, Tochigi-ken in order to re-visit the nearby Kurita Museum, before returning to my home base in Shinjuku.

Although it was a "mad flying scientist's tour", it will always remain one of my most memorable solo-adventures through one of the most beautiful "hidden" corners of the terrestrial sphere: The westside of the Tohoku District in Japan.

3.2B Visitations of the Sugadaira Space Radio Observatory through Saitama, Gumma, Nagano and Yamanashi Prefectures.

My FINAL REPORT on Phase I to JSPS would be incomplete if I would not be adding a section on the splendid and most carefully planned car tours in Prof. Takeo Yoshino's green Alfa Romeo, known of all over Japan with steering wheel on the left side. During my three last visits to the Kanto/Tohoku Districts of 1978, 1985 and 1986, Prof. Yoshino has troubled himself to make me enjoy some of the most learned guided car tours through the Japanese Alps starting in Kyoto via the Southern, Central and Northern Alps all the way to Sendai. In the following, I am selecting partial tours of the many car rides to Sugadaira which always followed another route, and piece them together to one representative round-trip.

Usually we would start out from the UEC Campus in Chofu-shi westward on the famed Chuo-Kaido to the Chuo-Kosoku-Dori via Fuchu-shi, Hachioji-shi, Otsuki-shi to Kofu and then use any of many possible main/side roads in northwestern direction toward Sugadaira. Here, I will be describing another variation through the Saitama-Gumma prefectures via the active volcano Asama-yama to Sugadaira.

B.1 Car-Tour UEC/Chofu-shi, RML/Koganei-shi, NTT/Musashino-shi, Tohoku-Jidosha-Do-Maebashi, Takasaki, Asama-Yama, Kumagai, Sugadaira

Although there exist multiple lane speed ways, turnpikes and tollways, usually stacked multiple stories high, through the densely packed downtown and suburban Tokyo, traveling by car is almost at any time during 6:00AM to 11:00PM a nightmare and without being fluent in reading Japanese characters, one better leaves left-handed driving to an experienced Japanese driver. Prof. Takeo Yoshino not only is an experienced driver, but he seems to know every side road wherever we went; and "detecting traffic slow-downs" far ahead, always found a non-congested rapid detour.

Instead of escaping westward from UEC/Chofu-shi, we drove northward along Tsurukawa-Kaido passed Jindai Tokyo Metropolitan Botanic Garden (fifteen minutes by foot from UEC-Guest house), the Radio Research Laboratory, Koganei-shi and the NTT Basic Research Laboratories in Musashino-shi before cutting across the Nerima-ku on narrow backroads, at times opening up to delightful famed shrines or temples with surrounding shrub (tsu-tsu-ji and fuji) gardens. Every important building complex including colleges, various research labs, like those of NASDA, were painstakingly identified until, after about ninety minutes (25 miles) we reached the entrance of the Tohoku-Jidosha-Do, one of the major National Japanese divided tollways, where cohesive traffic flows steadily at a speed of 100 km/hr.

Close to the exit near Maebashi, where we passed the extensive assembly halls of the Subaru Motor Company, we had lunch at one of the periodically interlaced Tollway Rest Places (Drive Inns) at a reasonable price. Although all kinds of maps, sightseeing brochures in Japanese are available at the tourist stores, there are almost NO English/German/French/Russian written materials available which is a real problem for any foreigner (!) and here I refer to the English version of

Teikoku's Complete Atlas of Japan (1985), Teikoku-Shoin Co., Ltd.
Tokyo, 29, Kanda Jimbocho 3-chome, Chiyoda-ku, Tokyo 101.

because it indeed is one of the best complete Atlas for reference of Japan. From Maebashi-Takasaki, we departed from Tohku-Jidosha-Do and drove along the Gumma-ken Rd 18 to Karuizawa and then along a beautiful mountain road twisting around the northern side of Asama-Yama (2,542 m) to a height of about 2,000 m on the Westside National Park with Volcano Botanic Garden. For me it was a real pleasure to see so many early spring-flowers and in particular various species of tsu-tsu-ji in full bloom. Prof. Takeo and his wife, both active members of the Japanese Alpine Society, are rather knowledgeable mountain flower amateur botanists and thus it was a real pleasure to strive through the maze of Herbaceous Flora paths (Pflanzen-lehr-pfad) below Asama-yama who released, periodically in three to five minute intervals, compact smoke puffs and occasionally also smoke rings to the great delight of our fellow naturalists.

Before embarking toward Sugadaira via a winding mountain road bypassing Tsumagoi, we admired the colorful display of the delicate Asama-Yaki vases some of which we now enjoy admiring daily at home.

B.2 Geoelectromagnetic-Seismic Field Trip: Sugadaira, Nagano, Matsushiro, Usuda, Nobeyama, Komoro.

The UEC Sugadaira Space Radio (Wave) Observatory is hidden away somewhat west of Sugadaira township, which over the past two decades has grown to become one of Japan's most famous ski resorts, surely not to the total liking of its multi-talented director Prof. Takeo Yoshino. Geographically, its location was ideally selected to create a Very Long Base Line radar site for the VLBI system Kashima (RRL), Nobeyama (UT, UK, UN), Usuda (ISAS) and Sugadaira (UEC). The observatory is well equipped with ELF/VLF, HF antenna systems for deep space observations and with satellite tracking/communications radar plus an 18m dish deep space radar system to be added in the near future. Several research associates and undergraduate/graduate research assistants labor under the able supervision of Mr. Ichihiro Tomizawa, PhD candidate (UEC) on a part-time/year-round basis either building from scratch or complementing available electronic equipment/instrumentation systems.

The nearby dormitory can house about ten senior scientists and 30 graduate research assistants and thus would be and is ideally suited to accommodate the scientists partaking in small Advanced Research Workshops. Sugadaira (1363m) is a lovely pre-alpine mountain village and is inviting almost the year-round with snow-capped peaks (2000-3000m) of the Northern Alps in the distant neighborhood. A local natural science museum provides insight into ecological/geological history of the Sugadaira valley and a Herbaceous Flora/Shrub Botanic Garden, maintained by the Tsukuba University of Science, Outreach Program is very pleasantly laid out placing extra emphasis on the surrounding coniferous tree species which to a great extent are dominated by various species of larches.

Instead of using our usual route, south-westward via Samada to Ueda along the Chikuma-gawa, we drove down the steep westward mountain side toward the capital Nagano of Nagano-prefecture, where the Chikuma-gawa flows into Japan's longest river, the Shinano-gawa, reaching the Sea of Japan at Niigata. Staying to the east of the river, we first visited Matsushiro Seismological Observatory in a side valley almost hidden under a cover of blooming cherry trees. (See Section 2.C). After traveling across the Shinano-gawa, we passed a massive land slide which not too long ago was created by earthquake activity with epicenter close to the Hoku-shin Micro-seismology Research Observatory of Tokyo University which we visited next walking down into the deep tunnel (see Section 2.C). For the next two hours we traveled along the Chikuma-gawa passed Koshoku, through Ueda, Komoro Iwa-mirata (where we visited the famed Prof. Yuh-ichi Akasofu's parent home, a corrugated tin shed to which he was born and raised) and drove up a sideroad to Usuda Deep Space Radio Observatory located in total isolation in the Sugadaira mountain range. It was my third visit to this fascinating deep space radio observatory which is surpassed in grandeur and technological perfection only by the Max Planck Effelsberg 100m dish radio telescope near Bonn, FRG-West Germany (See Section 2.C).

The next stop was in the upper foothills of Yatsugatake (2596m), where Prof. Takeo Yoshino has set up his electromagnetic ELF/VLF earthquake precursor loop

antenna epicenter telemetric recorder system next to a geomagnetic observatory of the Tokyo University, Earthquake Research Institute in a low radiation noise location (See Section 2.C). On our drive back from the winding mountain road we passed a Crematorial Shrine pleasantly set back in a valley with a rapid mountain streamlet singing an eternal tune for the mourning congregation dressed fully in black.

The last stop before sunset, in the late afternoon, was scheduled for the Nobeyama radio telescope interferometer facilities of the Japanese Universities, where I am able to take some splendid photographic shots of the various antenna systems (See Section 2.C), against the mountain peak setting of the Southern Alps (Koma-ga-take; 2966m). Here at Nobeyama we usually met a fairly large number of foreign guest scientists from Australasia, UK, Western Europe and North America who praised the hospitality of their Japanese hosts. On our ride back to Sugadaira, Prof. Takeo Yoshino at times chose one of the most exciting mountain ridge roads north of Komoro and south of Asama-yama, bypassing Samada to the north. Valleys were hidden under the mist and the various mountain ranges overlapped in various strong-to-paint bluish-grey pastel colors in which one or the other Japanese village was cozily embedded.

During such a day's research travel through the Chikuma-gawa valley dotted white and pink during spring time's cherry and peach blossoms, we enjoyed the industriousness and tidiness of the Japanese mountain rice and vegetable farmers. Both modern machine farming methods (in the valley) and still more traditional manual farming methods (mountain valleys) can be observed. To me, a son of a tropical agriculturalist, such days recalled the memories of my boyhood years in Southern China and Indonesia, and there like here near Sugadaira I felt as if I were somehow "at home".

During the long evening hours up in the directors office, we then summarized a day's events and discussed global research expansion topics (See Section 2.C).

B.3 Southern Nagano Prefecture Mountain Round Tour with Visit of Matsumoto.

Upon my suggestion that we may visit one day the Nihon Ukiyo-E Museum (JUM) in Matsumoto-shi, Nagano-ken, on a perfect late spring Sunday, Prof. Yoshino chose one of the most exciting mountain routes departing from Sugadaira down via Samada to Ueda at the bottom of the Chikuma-gawa valley and transversing the Shinano mountain ridge toward Matsumoto along the idyllically designed winding mountain road (Nagano-ken No 143). Whereas in the valley the tsu-tsu-ji had lost their flowers, higher up both the tsu-tsu-ji (azalea) and the fuji (wysteria) were in full bloom, the first in fiery reds and yellows and the latter in pastel blues, yellows and white—a sight I have not even seen around Japans most famous mountain, the Fuji ("wysteria") yama! The mountain farming village appeared medieval, and untouched by modern world since Japan opened her doors in the 1880s. It was a delight to be able to still be a witness to such harmony between nature's beauty and man's varied talents—the well-attended thatch-roofed village huts, fences and gardens; the neatly maintained rice paddies which were just prepared for planting the 1986 rice seedlings; and then the healthy, dear and modest looking peasants in their classic working kimonos. To me it appeared as if the Ukiyo-E wood print picture's of the buoyant peasant's life of Hiroshige, Hornoshobu, Hokusai and others just became truly alive again.

Although I had visited the Riccar Art Museum in the Ginza and the Ota Memorial Ukiyo-E Museum in Shibuya/Harajuku, it seems that the

Nihon Ukiyo-E Museum
(Japan Ukiyo-E Museum: JUM)
2206-1 Koshiba, Shimadate
Matsumoto-shi, Nagano-ken 390
81-263-47-4440

does possess one of the largest and most outstanding selections of about 100,000 prints. Only recently, did I discover a very fine selection of Ukiyo-E wood prints displayed in the Chicago Art Institute which matches the exhibition displayed in the ultra-modern Nihon Ukiyo-E Museum of Matsumoto.

On our return ride to Chofu-shi, we passed the lovely mountain lake Suwa with its various Optics manufacturing industries and when we approached the garden city of Kofu with its peach/cherry/apricot/pear/wine orchards via Nirasaki, the Tokyo-ward Sunday traffic enticed Prof. Takeo Yoshino to detour via Kawagu-chi-ko Lake, Fuji-yoshida, Tsura back onto the Chuo-Kosoku-Doro and back via Hachioji-shi to UEC. Unfortunately, it was cloudy and rainy for the last part of our travels and so we were not able to view Fuji-yama as we were able to enjoy during August 1978 and 1985. Yet, it was again a marvellous adventure winding through these heavily populated mountain valleys with ultra-modern villas, estates and modern superstructures demonstrating how to the east of Kofu and Fuji-yoshida a new aggressive technological Japanese style of architecture and living is replacing the ancient tradition of well-balanced harmony.

We returned home into the rainy monsoon season, and again I was reminded of the many Ukiyo-E scenes of dark clothed citizen rushing home under a sea of umbrellas with the street lanterns providing a spooky illusion in the misty rain-soaked atmosphere. I was home again at the cozy UEC guest house close to the Fuda-Ten Jin shrine along Jin-Dai Kaido joining Tsurukawa Kaido and leading to the Jin-Dai-Ji Temple and the neighboring Jin-dai Metropolitan Tokyo Botanic Garden along which our Sugadaira SRO excursion had commenced earlier on.

3.2C RESEARCH & CULTURAL TRAVEL FROM TOKYO STATION TO SHINOSAKA ALONG TOKAIDO WITH THE TOKAIDO-SANYO SHINKANSEN.

In this special travel report, selected research/cultural travel tours are collected which were organized in collaboration with Prof. Yasumitsu Miyazaki and his coworkers and graduate research students at Toyohashi University of Technology. The Tokaido-Sanyo Shinkansen provides the most convenient, comfortable and enjoyable means of travel between the main Japanese tourist cities of Tokyo, Nagoya, Kyoto, Osaka, Kobe, Okayawa, Hiroshima and Kitakyushu (Hakata), and at times during the peak tourist season it assumes an international character like the Orient Express. One would assume that international literature is available everywhere along this highly traveled route which, however, is not so as one may be surprised to learn even in cities as big as Toyohashi or Hamamatsu. Therefore, one needs to come well prepared in order to be able to interact most effectively.

Whereas research visits to academic governmental and industrial institutions within the Aichi Prefecture have been summarized in Section 2.B, closely related cultural research events are collected here.

C.1 Tokyo - Shizuoka - Hamamatsu - Toyohashi

This Phase I, Part 2 JSPS fellow tenure started with the long May 04-May 06 weekend (National Holiday: Kodomonohi) and thus I chose to visit Ueno Park with its museums and botanic garden facilities which included the Museum of Natural History and Science, the Museum of Western Art, The Buddha-Memorial (1200 years Buddhism in Japan) Exhibition, the Botanic Garden with the most outstanding Peony Exhibit I have ever seen.

It was a delightful day during which I learned a lot about Buddhism and its various Zen-Buddhist derivatives of Japan and the Buddha-Memorial-Exhibition needs to be praised very highly and I had the pleasure of becoming acquainted with a Zen-Buddhist scholar whom I enjoyed to meet later on several times discussing the influence of Buddhism on World religion.

I was, however, surprised about the poor state of presentation of the Museum of Natural Science & History and together with other foreign visitors to Japan we must sincerely request that the Japanese Scientific Community, at large, give some special thought on how to improve on this important matter.

I had stayed at the Shinagawa Prince Hotel near Shinagawa Station which I found to be not as convenient as, for example, the Shinjuku Prince or any other Hotel in Shinjuku, which I wish to reemphasize because it turned out to be remote from major cultural sites as well as to be impractical for transporting heavy luggage. Later on, I found out that in Japan unlike elsewhere all luggage is usually being shipped via Pickup/Delivery house-to-house Express which saves the inconvenience of logging heavy luggage up/down the long impractical staircases in railroad/subway stations.

On a rainy pre-monsoon day I took then off from Tokyo Station to Toyohashi with an unusually long stop-over in both Shizuoka and Hamamatsu, then finding out about the most important international iris collection at the Kama-Hana-Shobu-En garden in Kakegawa, Shizuoka-ken. Unfortunately, I missed visiting this superb exhibit of the Japan Iris Society which will have to be postponed to my Phase II or Phase III visits in forthcoming years. But equally well, I enjoyed the Shinkansen travel and viewing the "green tea" plantations in the Shizuoka prefecture.

Upon arrival at Toyohashi I was welcomed by Prof. Yasumitsu Miyazaki's able research staff, Drs. Mitsuo Yamaga and graduate students.

C.2 Cultural Research Travel in the Vicinity of Toyohashi: Atsumi-Hanto Peninsula, Horai-ji-san, and Ryo-Tan-ji

During my stay at Toyohashi University of Technology located to the south of Toyohashi on Atsumi-Hanto Peninsula on top of Hibarigaoka (Lark-hill), Tempaku-cho out in the rural farming area (watermelons, vegetables, pigs and chickens) one is rather isolated without car and due to rather infrequent bus commuter service to the downtown Shinkansen railroad station, and thus naturally close interaction with graduate research students arose.

Toyohashi Gi-Ka-Dai derives most of its graduate research students from top-ranking graduates of the National Technical Colleges which, like anywhere else, do provide some of the most talented engineering scientists and here I wish to recall the name of just a few of them

Haruo Miyawaki (Technologist)

Yoshihiro Matsumoto

Sei-ichi Nishimura

Shigeru Kobayashi

Moto-o Nakano

Katsuya Manabe

Yasuro Yamamura

Kihachiro Taketomi

and there also was a fairly large number of foreign exchange students from Iran,

Malaysia, China and Africa of which I will here name Khalil Kalantari and Zulkiflee Bin Mohd who both mastered the written and spoken Japanese language to the greatest admiration of their Japanese fellow students and professors with great skill.

It was a precious, friendly motivated group of graduate students who collaborated and interacted harmoniously at all times when I was around. Next to long hours of research discussions on electromagnetic imaging, fibre optical communications and traffic control radar analysis, I was invited to participate in three major outings which were priceless.

First, we visited together with Dr. Mitsuo Yamaga and Mr. Khalil Kalantari the tip of Atsumi-Hanto Peninsula, named Irigo with nearby ferry-harbor Irigo-Misa-Ki from where one could ferry over to the famous Ise shrines in Ise-Shima National Park. Along our way, we passed a seemingly endless chain of green houses and garden farms for vegetables, all kinds of melons, berries and flowers. There also were several memorial stones recalling near past typhoon and earthquake disasters, dating in part back to WW II, during which the Hamamatsu-Toyohashi-Nagoya area was almost erased by fire bombing. Hence, this entire area with the exception of a few isolated sections along the ancient Tokaido within Aichi-ken provides a rather monolithic reinforced concrete/cement box architecture which is outspoken ugly.

Yet, the nearby foothills of the Southern Alps provide for some of the most beautiful recreational areas and I sincerely enjoyed the Institute picnic at Horai-Ji-Zan National Park north of Toyokawa, where we also visited the famous Buddhist temples and Shinto shrines of Mount Horai-Ji-Zan dating back to the tenth century. These temples later on recalled memories when I was hiking up the Omei-San Buddhist temples near Leshan, Szechuan, P.R. China. My driver, the Malaysian student Mr. Mohd Zulkiflee Bin from Kuala Lumpur and our host students Shigeru Kobayashi, Yoshihiro Matsumoto and Moto-o Nakano made every effort to explore the unknown in nature and in the well-developing rice paddies, where egrets and cranes were abundant.

One of the most exquisite, delicate and beautiful manmade structures is the Zen-Buddhist temple with garden, Ryo-Tan-Ji, founded in 733 by the famed scholar and priest Gyo-oki. It was an absolute delight to enjoy the backyard garden displaying mountain/country scenes of Szechuan, the Omei-san area. We bypassed the famed Hamana-ko Lake and also visited the Ryu Gashi caverns, developed only as recently as 1981-1983 by a Mr. Sadao Toda introducing rather advanced electronic cavern illumination techniques which my hosts Yoshihiro Matsumoto, Sei-ichi Nishimura and Shigeru Kobayashi enjoyed just as much as I did.

After returning from this delightful cultural tour, I assisted my hosts in preparing for their bi-monthly student research paper presentation which was directed with great skill by research docteur Prof. Yasumitsu Miyazaki who always impresses me by his energetic, dynamic approach, width, breadth, knowledge and oversight of so many research fields.

In summary, during my stay at Toyohashi Gi-Ka-Dai I had the closest interaction on both research and social levels with the Japanese as well as foreign students who all had been very pleasant hosts. A special note of thanks is here extended to Dr. Mitsuo Yamaga who put a lot of effort into guiding the little too oversized number of graduate students within the research group of Prof. Yasumitsu Miyazaki, who due to his many important commitments can only spend little extra time with his students.

C.3 Research Interaction with Professor Yasumitsu Miyazaki and his Colleagues at Toyohashi Gijutsu Kagaku Daigaku

As active University Research Professors and Directors of Research Laboratories, all of us, wherever and whoever we are, never have enough time; and priorities must be chosen according to ones talents, needs and prerogatives in order to achieve maximum impact. I admire Prof. Yasumitsu Miyazaki for his tremendous intellectual abilities, his extraordinary memory and above all his managerial research talents. Working together with him and visiting the neighboring academic/government/industrial laboratories was a real delight, and a most rewarding experience. He opened the doors for me to visit the National Science Institutes in Okazaki and the various Research Institutes of Nagoya University including the famed Research Institute of Atmospheric, and I have expanded this interaction already with extensive correspondence (See Section 2.B).

I was especially impressed by the well-equipped research laboratories at Toyohashi Gijutsu Kagaku Daigaku on all possible levels. Next to Prof. Miyazaki's various laboratories, I was visiting regularly with Dr. Shiro Usui, Professor of Physiological Electronic Engineering, who completely agreed with me that more must be done on introducing high-standard senior undergraduate/post graduate courses in the areas of environmental quality and control based on advanced fundamental courses which should include one course each on "air quality/atmospheric electricity", "water quality", "acoustic/electromagnetic radiation quality", "engineering esthetics" and "health quality". Certainly, too many valuable curriculum hours are nowadays wasted on social and political "soft sciences" courses which do not address the real issues a modern engineer will be confronted with in tackling the very complex problems of environmental control for the survival of the human race and all living creatures on this terrestrial sphere.

In summary, I sincerely enjoyed my stay at Toyohashi and wish to thank Prof. Yasumitsu Miyazaki and Vice President Dr. Yoshimasa Furuya for letting me use the pleasant guest house facilities.

C.4 Research Travel to Kyoto, Nara and Osaka

There are three cities rather similar in layout, history and beauty: Florence, Kyoto and Dresden; and, it is always rewarding to know that Kyoto still exists untouched in its original grandeur. During this Phase I tenure, I had spent one long weekend in the Kyoto-Nara area joined by the Zen-Buddhist scholar whom I had met earlier on during the 1200 year Buddha Memorial Exhibit in Ueno Park, Tokyo. It was a rewarding pilgrimage and we visited temples and gardens and attended a Buddhist funeral ceremony of a renowned scholar outside Kyoto. His knowledge of world religions and then also of nature astounded me and I felt a deep sense of peace and admiration for the Japanese cultural and religious contributions. On our travel into the farmland, I especially appreciated the "wet flower iris (hanashobu)" gardening.

After this weekend interlude, I ended up for another busy day in Osaka, where I first met with Dr. Yoji Furuhashi, Director of the Optical and Radio Science Research Division of ATR International (see Section 2.B) with whom I discussed future expansion of academic research interactions once the new University/Industry R&D complex in the Kyoto-Nara-Osaka triangle has been established.

Visit of Osaka Daigaku

Thanks to the kind preparations by Dr. Nagayoshi Morita of the Department of Communications Engineering (Tsushin Kogaku-ka), it was possible for me to visit Osaka University and have some lively research interactions with his colleagues Drs. Toshitaka Kojima, Dr. Makoto Tsutsumi, Dr. Kazuo Tanaka (Gifu Daigaku) and Dr. Yoshinari Ishido. The research interests in applied and basic electromagnetic theory of this very active research team, strongly influenced by their past leader and current President of the University of Osaka, Prof. Dr. Kumagai, are strongly overlapping with ours. Certainly, increased future research interaction is desirable.

My visit to Osaka Daigaku was crowned with an appointment to meet again with President Kumagai, who impressed me by his vision, overview and deep understanding of complex issues facing modern engineering & applied sciences education and the role of academia in the triangle "government-academia-industry". In great detail, the concern for improving environmental quality was discussed.

Visit to Osaka Denki Tsushin Daigaku

After an entertaining lunch with his very able and active colleagues, Dr. Nagayoshi Morita guided me to the Osaka University of Electrocommunications, where we met with Prof. Masayuki Hashimoto who is pursuing scattering and diffraction analyses of optical transmission devices. Of particular interest to me, however, were the radar path communications studies of his colleagues, Dr. Yasuyuki Maekawa and Dr. Nion S. Chang, who are involved in terrestrial-space communications research collaborating with the Computer Service Company (CSK) in Setagaya-ku southwest of Tokyo. Especially the 30 GHz transmit/20 GHz receive circular polarization transmission studies looked very interesting in the context of other similar research carried out at DFVLR-Oberpfaffenhofen, FRG and NASA-Greenbelt.

My visit to Osaka was concluded with one of the most memorable evenings in Osaka, with umbrellas through the steady monsoon rains under faint street light illumination, again recalling the marvelous wood prints of the various Ukiyo-E masters of the past.

C.5 My First Visit to Kyushu Island and Attendance of the 1986 May 22/23 Meeting of the Japan Institute of Electronics & Communications Engineers, Tokyo Chapter at Kyushu University, Fukuoka, Kyushu.

Thanks to the generous hostship of Prof. Takeo Yoshino, I was able to visit Kyushu Island and visit the Kagoshima Space Center at Uchinoura, the volcano Sakura-jima and the enjoyable city of Kagoshima before attending the 1986 May 22 Meeting of the Japan IECE, Tokyo Chapter Meeting by the kind invitation of Profs Naohisa Goto and Makoto Ando of the Department of Physical Electronics, Tokyo Kogyo Daigaku.

Visit of Uchinoura and the Kagoshima Space Center

Together with Prof. Takeo Yoshino, we first had a pleasant flight from Osaka Intl. Airport to Kagoshima, from where we traveled by bus around the northern shore of Kagoshima-wan via Aira, Kokubu, Miyakonojo, Osumi, Shibushi, and Koyama to Uchinoura; thus encircling Sakura-jima and observing the destruction caused by the lava ashes it is continuously spewing into its surroundings for the past several years. It was a very educational tour through almost but not fully

subtropical flora with rice paddies dominating the scenery whenever we entered the lowlands or wider valleys. Prof. Yoshino, very familiar with almost every single sideroad, was the best guide anyone could find for introducing me to the life and beauty of the isolated fishing harbor village Uchinoura where also, like in the wider Shibushi-wan sub-ocean farming was carried out on a grand scale. We stayed at a Japanese Youth Hostel engaging into very lively discussions with other guests, who either traveled on foot, bike or motor vehicles.

On top of the hills to the east, we could see the large tracking and communications antennas of the ISAS, Kagoshima (Rocket Launching) Space Center (see Section 2.C), where we spent a full morning before traveling via Koyama, Kanoya, Tarumizu around the southern foothills of Sakura-jima to Hakamakoshi and by ferry back to Kagoshima.

Next to the very impressive rocket launching facilities with its colossal space-tracking radar electronic facilities, as described in Sect. 2.C, I in particular admired the serene beauty of the coastal landscape with the Pacific to the east and the Uchinoura-wan deep down on the western steep hillsides. Dr. Sareo Watari and his engineering staff introduced us to all the facilities and the local space museum which provided a very good overview of Japan's contributions to space exploration.

Our car ride back to Kagoshima through very fertile farming pastures of great historical importance for the development of Japanese culture with excarvations dating back to pre-stone age, was a special gift, and within one afternoon I absorbed the knowledge of many textbooks written about the Japanese way of life, history, social and militaristic structure of the past. So, for example, was our visit to the famed (WW II) Kanoya Japanese Naval Air Force base with its famous museum on relics of the near past (about 90 years) Japanese military history a real eye-opener. I came to understand why and for which intermingled religious, social and national feelings the famed Kamikaze (Godly winds) fighter pilots are still adored so highly, and more so did I learn that we of European/North American background better try to understand more rapidly the roots of the Japanese way of life which from a narrow view angle easily can be misinterpreted as facistic nationalism which is certainly wrong. After our visit to the perfectly maintained facilities of the Kanoya Naval Air Force base, we were taken for a leisurely ride along Kagoshima-wan through Tarumizu to the Hakamakoshi Volcano Observatory of Kyoto Daigaku, at times, driving through thick clouds of lava ashes completely obscuring our vision. The roads, the fields, the roofs, the cars, etc. all were covered with layers of recent blue-greyish-black ashes which are rather acidic and can cause considerable erosion damage even to plastics and window glass. For me, the visit to the observatory was most stimulating and I sincerely enjoyed the deep knowledge Prof. Takeo Yoshino and his colleagues of the Kyoto University Geophysics Institute. Before departing for Fukuoka the next morning, we discovered the beauty of this almost sub-tropical garden city of Kagoshima with its beautiful Kagoshima Botanic Garden which so much recalled memories to the coastal towns of New Zealand or Queensland/Australia. I was quite intrigued with the history of Kagoshima and which the role of the famed but unfortunate general had played.

Attendance of Japan IECE, May 22 1986 Tokyo Chapter Meeting at the Kyushu University, Fukuoka

We had the pleasure to stay at the Hakata Miyako Hotel opposite of and overlooking the terminal Hakata-Station of the Tokaido-Sanyo Shinkansen railroad to Tokyo, one of mankind's greatest achievements in transportation of this century.

The meeting in the Faculty of Engineering of Kyushu University was very well attended and I was introduced first to Assoc. Prof. Mitsuo Tateiba and Prof.

Otozo Fukumitsu, who introduced me then to his former doctoral student, Dr. Mitsuru Tanaka, Assoc. Professor of Oita Daigaku, Electronics Engineering Department, and currently Visiting Professor here at UIC.

During that very lively meeting with scientific presentations of a very high level, I enjoyed meeting many old acquaintances and friends including Dr. Yoshiro Hayashi, Nihon Daigaku, Profs Goto and Ando, Tokyo Kogyo Daigaku, Dr. Masami Akaike, NTT Labs, Yokosuka, Dr. Hiroshi Yokoi of Kokusai Denshin Denwa (KDD), Osaka, et al. It was a real pleasure to sit on the back bench and observe a meeting in the Japanese language, where however almost everyone was capable of either speaking the English or German languages rather fluently. After my invited lecture in the late afternoon, I enjoyed the very knowledgeable questions on recent advances in Electromagnetic Inverse Scattering and Radar Polarimetry which extended far into the social gathering of the early evening. Here, I would like to take the opportunity and thank my Japanese hosts for their kind invitation and for presenting me with such a precious vase from Arita-ken so well selected by Drs. Goto and Ando.

Our Kyushu Island visit was then concluded on Friday, 1986 May 23, when we were returning to Tokyo-Haneda Airport in the morning in order to attend the concluding session of Friday afternoon on Polarimetric SAR Imagery by Dr. Dianne Evans of JPL, Pasadena during the International Symposium of Space Science & Technology.

3.2D Cultural Research Travel to Guanzhou, Guangdong Province, Xian, Shaanxi Province, Cheng-du, Meishan, Emei and Leshan, Sichuan Province, P.R. China

During my second visit as CAST fellow under the umbrella of a U.S. Midwest University Consortium for International Affairs program I was able to visit various cultural as well as academic and industrial research facilities within the provinces of Guangdong, Shaanxi and Sichuan of the Peoples Republic of China. Although these research travels were conducted under a separate program, I do include the reporting here in order to appropriately enlarge the scope of my JSPS fellow award program for the true benefit of all my sponsors: the Japan Society for the Promotion of Science, the P.R. China Association for Science and Technology and the U.S. Midwest University Consortium for International Affairs as well as the US Naval Research Office, Far East Branch Office.

D.1 Transition from Japan to P.R. China

In a certain way, even I as a born German in heritage, felt great relief in escaping for a while the stress and strain of the Japanese sphere of life, filled with super-perfection, absolute punctuality of appointments, deadly adherence to approved and also not approved schedules far beyond of which I was subjected to during my formal education in FR Germany (which is still being considered the absolute standard!!!), and an almost unfriendly, cool business-like stiff social atmosphere, where people seem to most foreigners joyful only after being overly intoxicated. By air-jetting from Tokyo to the mainland (Shanghai or Hongkong = Xiang-gang) one gets thrown into another extreme, that of seemingly endless chaos, stoic relaxation, loss of sense of time, "ever-smiling and happy China-people" in a never-ending stream of bicycles or pedestrians, reaking with the odor of overcrowded encampments, greasy spoons, ever-blowing dust of central-Asian topsoil, etc. From the very first moment, with the first step on the soil of this great country, the People's Republic of China, it became sadly apparent that the recent past "Cultural Revolution" put China to its knees and the metamorphosis back into a stone-age/pre ice-age culture was almost perfected

by the Gang-of-Four and their worrisome large number of enthusiastic disciples blindly following a gospel of Chairman Mao's "Little Red Book"!

Recalling my early boyhood experience under Japanese and Chinese domination, it makes sense to me to reminisce and recall the paths China and Japan have taken since the end of WW II. Whereas Japan with the guidance of General Douglas McArthur and his competent staff was invited to integrate into the advancing modern world of scientific and technological achievements, China with the guidance of Chairman Mao was led a path back to primitivism, step-by-step eroding and erasing man's hard-fought cultural, scientific and technological advances. The rift between China and the modern world thus was ever widening and especially between China and Japan. It so happened that during my stay of 1985 in P.R. China our former President, Mr. Richard M. Nixon, also enjoyed his tenure as State Visitor. Irrespective of the past saddening US history, the courageous world-political steps of that visionary president will have to be honored most respectfully in the future in that it was the action of his administration mainly that assisted the recent past chairmen and the current Chairman, Deng, Xiao-Ping, to reverse the gears and to put an end to that nonsensical destruction of man's hard-fought battle for the advancement of culture, society, science, and technology.

Before summarizing my findings of specific research travel events, it is worthwhile emphasizing here that, whereas, in almost every department of industrial science and technology, Japan has "pulled away" and has undoubtedly become the world's leading force in the advancement of technology, the People's Republic of China, whose population recently surpassed one-billion, is the most backward superpower as regards education, science, transportation and technology. Yet, during my visits to both Japan and China, it was very apparent that these two technological anti-podes are being pulled together with increasing pace like magnets of opposite polarity: China requires advanced HI-TECH Science and Industry, and Japan requires a nearby expansion space! We North-Americans cannot reject, but must agree with former Prime Minister Trudeau and former President Richard Nixon that it could be a grave mistake if not a selected group of knowledgeable Canadians/US citizen of all spheres of life are given the opportunity and means to monitor simultaneously, the political, the social, the religious, the scientific and technological events governing the interaction of these two leading supreme superpowers of tomorrow. It is not sufficient that only selected groups of Japanese and Chinese visit the West, complementarily it is high noon that more of us from the "Occident" and "Northamerica" get deeply involved in the daily happenings of the Northwest Pacific Orient, which in turns, will require the expansion of existing scholar/fellowship programs for foreigners to come to the Northwest Pacific Orient and be given the very essential opportunity of visiting Japan, Korea/Taiwan versus PR China/Vietnam simultaneously.

The badly needed action of increased interphasing of Occidental/Northamerican with Japanese/Chinese researchers on a one-to-one personal level must, therefore, not be viewed as one of treason, but to the contrary, is desirable for self-defending purposes of the future survival of mankind and, particularly, the free Nations like foremost the United States of America and definitely also modern Japan which, by the grace of God, was given a General Douglas McArthur to direct inter-pacific collaboration in a new direction of peaceful interaction. I am very convinced of the fact that the Japanese people are grateful, one-by-one, and with their most admirable Emperor Hirohito, are destined to become flagbearers of this spirit in order to tear down the ugly fences still separating

the two great nations of Japan and China, and at the same time permit the Occident and Northamerica to play a major role in this currently developing event. Namely, during my visit to the People's Republic of China, I found a desperate longing for true friends, loyal to God missionaries, honest businessmen, loving teachers and professors, able scientists and innovative technologists to pull this great people, who have given so much to the World, and Japan in particular, out of the deep mess of the cultural revolution which can be compared on the level of mankind's hard-fought battle for the advancement of science, technology, society and culture, only to a nuclear disaster far surpassing the material destruction of Hiroshima, Nagasaki, Chernylbol and what we still will have to endure.

We all, one-by-one, must reach out, embrace each other in good will and understanding and we should be happy to work together. The recent contra-revolutionary events on the Chinese campuses, which already started during my visit to Guangzhou, Xian and Cheng-du, clearly demonstrates the longing for true democracy and honest friendship without pretence and national greed for creating a more liveable future for the people of the Pacific Orient.

In this spirit, I request that my Japanese hosts, Professors Kyohei Fujimoto, Yasumitsu Miyazaki and Takeo Yoshino understand and accept the addition of my research visit to Xian, Shaanxi Province, P.R. China into my JSPS fellow award program and have the Japan Society for the Promotion of Science agree to the integration of my JSPS-CAST tenure under a MUCIA program. Similarly, I request that my Chinese hosts Prof. Lin, Shi-Ming, Prof. Mao Yukuan and Prof. Yang Ru-Gui offer their deepest understanding, assist us in tearing down misunderstandings created during and after WW II, make heal the terrible wounds which as I have witnessed still exist and must be recognized by all of my Japanese friends, and invite my Japanese hosts to their campuses.

D.2 Transfer Hong-Kong-Guangzhou-Xian

For me it is always exciting to revisit Hong Kong, the Pearl River(Zhu-jiang) and Kanton (Guangzhou) and to recall memories of my boyhood. This entire area of southwest Guangdong Province and Hong Kong (Xiang Gang) is continuously undergoing modernization changes, and Hong Kong of today may be one of the most advanced metropolitan centers with its internationally reknowned retail/whole-sale stores covering all possible commodities and electronics equipment surpassed only by a few isolated specialized shopping centers such as the electronics center Akihabara or the gigantic book center Kanda Jinbocho in Tokyo, to mention just a few. Yet, whereas in Tokyo, one need not worry to make a "really bad deal", in Hong Kong one better watch out for pick-pockets, bad deals, etc. And, unfortunately, this kind of sloppiness in business and social dealings which are still common encounters anywhere on the Chinese Mainland is certainly distinctly different from the Japanese approach. Therefore, I personally love to do my "international shopping" in Tokyo, where I can bet on good deals and not in Hong Kong. Thus I was quite happy to leave Xianggang as soon as possible on Guangzhou-Jinlong railroad, through the rapidly modernizing New Territory and the westernizing agricultural development zone around Shenzhen, which also presents one of the more beautiful and exciting train travel routes in Asia. It is interesting to note that although the far majority of passengers are of Chinese origin, there is a very high number of multi-bilingual occidentals and Northamericans, but next to the Xiang Gangese the Japanese always seem to outnumber all other foreigners traveling in our out of Hong Kong.

In Guangzhou, I was welcomed by Mr. Mei Wei-Min of CATIC at the immensely over-crowded Guangzhou Railroad Station, and hosted in the newly opened Dong Shan Hotel where the manager, Mr. Lu Cheng-Ming took excellent care of me and made sure that I was able to visit and see what I had desired to see including the Foreign Language Bookstore on Beijing Road, and the main down-town shopping area. I found the traffic remarkably organized, the police very strict versus traffic violations and jay-walking. Guangzhou still is as puzzling and huzzling a business center as it has been, most likely, for centuries. Most attractive, however, is its exceptionally large number of "Five-Star" Chinese Restaurants such as the Dongjiary, Yeweixiang, Jianglan Lee, Likofu, Yiyuan and Taipingguan to which I had been invited during my recent stays. I also visited Shawian Island, where at today's Baitian's (white swan) Guesthouses must have been the British Hospital, where my mother had been active during the early 1930ies and again in 1948/1949.

Next to visiting the impressive Dr. Sun Yat-Sen Memorial Hall, the Huang-Hua-Gang Memorial, etc. I was able to visit the Zhong Shan University witnessing many small demonstrations which, as I found out later, were already forerunners of the recent student unrests requesting more democratic freedom and I wish to add here that, we foreigners particularly from North-America, were welcomed openheartedly and with enthusiasm on any campus I have put foot on, very different from Japanese campuses, where a cool indifference seems to be displayed generally toward westerners.

D.3 Cultural/Research/Visit to Xian, Shanxi

Certainly a visit to ultra-ancient Xian, with its discoveries (1958) of the 6000 year old Yangshao culture along the Weihe-Huongha river valleys, is one of the most exciting historical research expeditions an engineering scientist ought to carry out. My hosts of the Northwest (Xibei) Polytechnic University, Xibei Telecommunication Engineering Institute, Xibei University, Xian Geological Institute and the Xian Jiaotong University certainly have been remarkable hosts; and during my heavily packed daily lecture program (often nine hours per day) still managed —during the noon break—to have me visit the most interesting ancient central city and surrounding parks such as the Bell Tower, the marvellous Shaanxi Provincial Museum with its impressive forest of steles and stone carvings, the Xianyang Museum, the Dayan and Xiaoyan Pagodas, the Grand Mosque of 742 and the mighty city wall dating back to the Ming dynasty (1374-8). It must have once been a most beautiful city with flowering gardens and impressive palaces such as the Xingong Park. And, above all, after extensively visiting many cultural historic sites in Japan, I personally found great affinity of the Japanese arts and culture especially to Xian, Xianyang, Qian-Xian, San Yuan, Longuan and Chan'en of Shaanxi Province.

All of us, from the Occident, from Northamerica, and particularly from Japan, we must contribute our best to see to it that this once beautiful imperial/cultural center of man's greatest achievements (as may be witnessed still today by viewing the Museum of Qin dynasty's pottery figures), be rebuilt, retained and made a center of global universal studies just like Kyoto Daigaku, Tokyo Daigaku or Tohoku Daigaku.

However, although every effort must be expended in order to rebuild this unique cultural relique, it is not a very hospitable place and the dust loess blowing down from the Himalayan, Tibetan and central Asian mountain plateau from

west toward the east with steady daily persistence as it must have been blowing for the past millions of years or more, i.e. Xian like almost every single Chinese city, village, hamlet, etc, is permanently dusty if not even dirty due to the thick layers of loess (fertile topsoil) adding a blanket of almost one centimeter deep a year or more in the Weihe valley. Thus, not only in Xian but almost all over China, there blows the dust loess from west to east and one just has to "squirt one's eyes" to reduce unbearable itching of the retina which for the particular species of man living east of the central Asian plateau may have caused a permanent mutation and provided them with the eloquently beautifully shaped almond eyes (my guess!). Thus contrary to Japan, being somewhat removed, and gifted with countless resources of natural fresh water, one finds China not to be very clean and tidy and its people less caring about absolute cleanliness and German-Swiss-like tidyness, i.e. all of the campuses of educational and research institutes are, may I describe it just as it really is: dirty, dusty and rather uncared for inspite of the existence of thousands of quasi-unemployed people who could be put to useful work. Here, however, I must reemphasize that the campuses of Japanese Universities are also unnecessarily dirty and untidy. During my stay in Xian, I was very happily surprised by the visit of Mr. Zhang, Yi-Min and Mr. Osamu Kawabata, two very brilliant post-graduate students of Professor Kyohei Fujimoto of Tsukuba Daigaku. Doctoral candidate, Mr. Zhang Yi-Min, who had never been in an English-speaking country spoke almost a perfect English tongue and was also fluent in German and Japanese, is a very remarkable young scholar and former student of Professor Mao Yukuan, who has impressed me most deeply. So also his able friend, Mr. Osamu Kawabata, another brilliant Japanese M.S. student of Prof. Kyohei Fujimoto of whom, I am certain, we will still be hearing and reading a lot in the future. Both of them attended many of my lectures and were welcomed clearly by my chinese hosts.

Especially Professors Lin, Shi-Ming, Ge Dao-Bin and Yang Ru-Gui arranged for me, next to visiting their academic and other government/industrial research institution (see Sect. IID), separate full day tours to (i) the East for viewing Lin Tong with its Hua Qing hot springs, the Qin-Shi-Huang Mausoleum with its Museum of Qin Pottery Figures near Mt. Lishan and the Banpo Museum (ii) to the Northwest across the Weihe River for viewing the Xian-Yang Museum and the many ancient tombs of Huo QuBing, Maoling, Yang Guifei, Qin Xian, Qian Ling, Zhao ling, etc. During my next visit I am looking forward to revisiting Chang'en with an extended tour to Mt. Nanwutei and Mt. Guhua to the South.

Whereas the cuisine of Guangzhou is about the best anywhere that of Xian leaves a lot to be desired in every respect. Thus, I was very excited to learn that my next cultural research visit together with prof. Lin, Shi-Ming is going to be directed to Cheng-du, Emei, and Leshan at the confluence of the three famed rivers of Qing-Yi, Min-jiang and Dadu.

D.4 Cultural Research Visit to Chengdu, Meishan, Emei and Leshan, Sichuan Province

One of my most exciting train travels ever was the twenty-hours limited express from Xian via Meixiang, Fengxiang, Paoki and across the Tsing-Ling Shan and Tapa Shan mountain ranges to Chengdu leaving at about 15:00 and arriving the next morning at about 11:00 am. We departed on a rainy monsoon afternoon and because the Xian Railroad Station was under construction, we had to wade through knee-deep muddy waters (no pavement close to the train station) and press through an endless wall of "onlookers" and possibly delayed travelers.

Whereas the coaches of the Japan Rail Line are always in perfect clean and orderly conditions, here in China one better come prepared in leather working jeans because, the dust loess and the smoke of the steam engines just get through the badly closing sliding windows and doors of totally overused coaches. We were four to a First Class sleeper, a Swiss geologist from ETH Zürich with his Chinese research colleague from the Beijing School of Geology, Prof. Lin, Shi-Ming and myself. The neighboring compartments happened to be occupied either by Japanese or Northamerican scientists, engineers and students plus their chinese academic/industrial guides with all of whom we soon engaged in extensive discussions throughout the night.

First, the train slowly wound through the Weihe river valley to Paoki and then started its up-hill battle into the Tsinling Shan mountain range. It was a very educational tour providing an excellent overview of Chinese farming in the area. In drastic contrast to Japan, I found the fields and paddies very untidy, disorderly and not neat along the Weihe river which however changed totally once the train entered the Chengdu plain of Sichuan in the early morning which were in perfect tidy and neat conditions—a real pleasure to view and photograph. The main building material is brick and of a rather inferior quality as one can see disintegration even on newer brick building structures. The orange-red burned clay of the bricks well matches the reddish-brown dust loess blowing down from the Central Asian mountain plateaus observable at times even during night time and all the way down to the Minjiang valley in Southeastern Sichuan. Somewhere close to the city of Nancheng, north of the Tapa Shan mountain range, we got badly delayed due to the derailment of part of the train which must have affected the last few coaches in particular. Anyhow, after a lot of turmoil and loud speaker sing-song, shouting and encouragements, we got again going and arrived only with a few hours delay.

Chendu is a very beautiful city and indeed has a lot to offer in cultural sites such as the Du Fu's Thatched Cottage park, the Qingyang Palace, the Nanjiao Park with the eloquent Temple of Marquis Wu and the Wenshu Monastery of which the Zen-Buddhist scholar, I had met earlier in Tokyo, Kyoto and Kamakura, had a lot to report of similar to recalling the importance of the temples of Mt. Emei and the Grand Buddha Temple of Wuyan, Ling Yun hills, as well as the Mahao Rock Tomb which we were to visit later.

In Chengdu we paid a visit to the Sichuan University as well as the Southeastern Radio Engineering Institute before passing through Southwest Jiao-Tong University near the city of Emei. Our cultural research guide Mr. Li, Zhi-Tin was an outstanding instructor and I will never forget the eighteen hour car round tour from Chengdu to Meishan (with visit of the Sansu Shrines), via Xia Jong to Emei (visit of SW Jiao-Tong University) and Mt. Emei rising over 3000 m above sea level. Not only in China but more so in Japan I was told many stories about the Holy Emei-Zan with its twenty or more temples. Although unprepared I held breath with my chinese hosts and all of us reached the Jinding (Golden Summit) temple in healthy condition, and we all agreed that indeed it is one of world's most beautiful sceneries with brilliant waterfalls, flora and fauna, butterflies of unequalled beauty, bats, hummingbirds, and statutes, monasteries and pagodas. Although our driver found a back road short-cut, around this mighty temple system of Emei-Zou, it is worth visiting many times, and I am encouraging all of my Japanese hosts to join our Chinese hosts to honor many famed Buddhist scholars who have contributed so much to the advancement of knowledge and human understanding. Before returning very late at night via Meishan to Chengdu, we

also visited the grand Buddha of Leshan and paid a visit to the famed city of Leshan at the confluence of the Dadu and Minjiang river, where my mother had been active in the Methodist or Lutheran mission hospital during 1934/5. It was a great day for me to visit this lovely river town of which our mother was recalling so many human encounters with the poor and diseased of the lower Chengdu plains.

After returning to our Jinjiang Hotel along the Fuhe river, we met with a group of Chinese and Japanese scholars who had been spending several days enthusiastically recalling their pleasant encounters at other nearby cultural sites such as the Du-jiang-yon irrigation system along the Minjiang near Guan Xian the Baoguai monastery and walking trails along the Long-guan mountains.

In summary, Sichuan certainly is a rich and beautiful province with beautiful and well-humored people who have contributed above all a spicy yet very well becoming cuisine.

D.5 Departure from the People's Republic of China, Return via Hong Kong to Tokyo and Chicago

At the relatively small but well laid-out airport of Chengdu I parted from Prof. Lin, Shi-Ming who had been a most wonderful host and it was a real pleasure to be together with him again after our recent six month research collaboration in our UIC-EECS Communications Laboratory in Chicago. He strongly supported our common objectives to expand our research interaction to include my Japanese JSPS-hosts Prof. Kyohei Fujimoto, Yasumitsu Miyazaki and Takeo Yoshino in academic and research projects of mutual interest.

When I then arrived in Guangzhou, a tremendous typhoon was battering the coastline of southern China and I thought I was lucky that I had to transfer to the Guangzhou-Jiaolong railway in the evening. It was pouring down madly and with the aid of several chinese post-graduate students departing for visiting scholarships to Austral-asia and Northamerica I was able to transfer safely from the Baiyun Airport to the Guangzhou railway station because my official guide Mr. Mei Wei-Min of CATIC had to attend to duties at the typhoon disaster prevention office of Guangdong.

Thus wading again through knee-deep running streams of water we made our way through to railroad station and found our reserved seats in the Xianggang Limited Express. Delayed by more than two hours we finally took off into the direction of the eye of the typhoon. The torrents of rain battered the air-tight windows of the air-conditioned coaches and caused the electric lights and the air conditioning to cut out almost once a minute. Again, very badly delayed we reached the main bridge over the Zhu-jiang to be informed that due to the typhoon, the bridge would be unpassable and we had better transfer via chunks to the other side, where another train was waiting for us. It was a real ordeal and without the assistance of the chinese students I would never have been able to finally arrive in Victoria Station of Hong Kong with six hours delay at 2:00 am in the morning. Especially I thank Mr. Li, Kao-Qing and Mr. Ling, Xing-Wei for their selfless assistance, in not only ferrying me but also all of my separate eight pieces of baggage safely across the Pearl river which more behaved as if it were alive with wild sea dragons.

It was good that I had made reservations at an outstanding hotel such as the Shangrila which made up for the high price (one of the most expensive in Kowloon), provided me with the desirable assistance to get to the airport in time

on the next morning at a very close call. As a result of this adventure, I suggest that anyone travelling in or out of Xianggang to P.R. China add an additional one day before entry into and two days after the exit from PRC. Luckily enough, our plane was also delayed at the Kowloon International Airport, where many hangars had been badly damaged and several large carriers were disabled by the falling debris during the monsoon-typhoon.

Our flight from Hong Kong to Tokyo-Narita across Taiwan was also rather bumpy, yet at times the clouds opened up and I was so able to take some excellent photographs of the Changkaichek airport, over which we strato-ferried, and then much later of Kashima, being able to identify the terrestrial-satellite communications radar antenna systems, before reaching Tokyo-Narita Airport with about five hours delay.

Tired out from this two-and-half day ordeal, I then reached the guest house of Denki Tsushin Daigaku in Chofu-shi rather late on Sunday evening. I guess, still under the visions of the chunk-ferry across the wild Zhujiang (Pearl river), I was suffering the nightmare of having lost my passport, airline ticket and traveler cheques during transfer at either the Narita Airport or Shinjuku Airport bus terminal stations, then starting a wild goose chase for the lost objects. In vain, even a major radio search of the police officer on duty during midnight hours at the Chofu-shi main police station together with Prof. Takeo Yoshino did not reproduce these objects—which luckily enough I then found in my "water-tight precious book handbag" into which I had transferred all important documents before leaving the Xianggang limited express on the Guangzhou side of the Zhujiang. With deserved humorous scolding, Prof. Takeo Yoshino then booted me into bed to get a few long overdue hours of deserved rest.

Then on July 15, 1986 together with Professors Takeo Yoshino and Kyohei Fujimoto we visited the Office of the Japan Society for the Promotion of Science to bid a Farewell and Promise for "Auf Wiedersehen" especially to Mrs. Yuko Furukawa, who had been so most helpful during my entire stay of this Phase I tenure of my JSPS award fellowship.

I sincerely wish to thank them all for their congenial assistance.

IV RECOMMENDATIONS AND SUGGESTIONS FOR PROGRAM IMPROVEMENT

Although I found that almost all aspects of the visiting scientist/scholar programs administered by the Japan Society for the Promotion of Science are laid out in all minute detail and are being administered meticulously to the point, there are many suggestions which I wish to recommend for possible consideration.

Because of the diversified nature of "weak areas" of the program, I wish to categorize the problems under four major headings:

- 4.1 Assistance for the Visiting Scholar from abroad to Japan
- 4.2 Provision of Carefully Selected Reference Material
- 4.3 Improvement of University Campus Guest House Facility
- 4.4 Improvement of University Campus Facility
- 4.5 Improvement of Environmental Quality
- 4.6 A Japanese Institute for the Promotion of Japanese Language and Culture

4.1 Assistance for the Visiting Scholar from abroad to Japan

Whenever I was dealing with JSPS fellows in Japan or abroad, I found that those scientists and scholars were carefully selected, of very high international standards and in many cases highly reknowned researchers, who deserve to be treated with the highest degree of respect and admiration. Most of us Senior Scientists have to adhere to very tight time scheduling satisfying very many different committments which requires much more flexibility in settling time schedules, and also more efficient means of ferrying around in Japan.

In addition, the monthly stipends provided by JSPS in comparison to the living costs are not on a fair equitable level and certainly require respectable increases in order to make up for the inflationary cost increases and Yen versus dollar re-evaluations. Therefore, I would like to make the following suggestions:

4.1.1 Personal (Bilingual) JSPS Identification Pass

Every JSPS scholar from abroad visiting Japan be given bilingual cultural identification and similar to that provided, for example by the Alexander Von Humboldt foundation (see copy attached) clearly spelling out

- i) identification of the scholar (dates/place of birth, country of citizenship, personal biodata (height, color of eyes/hair, etc.), photo--- in English and Japanese;
- ii) purpose of the mission of JSPS and that the holder of the "CULTURAL IDENTIFICATION CARD" is a guest of the Japanese government and should enjoy the assistance of all National Officers;
- iii) starting and completion dates of mission.

4.1.2 Flexibility of Dates of Tenure of any JSPS Fellowship

Due to the multi/inter-disciplinary research involvement of many selected fellows, their broad set of local university and national responsibilities, increasingly more will require more flexibility of finalizing the program schedules, distribution of the program over many years, etc., and therefore the

following is suggested:

- i) JSPS fellowships be distributed over a three-year duration with annually phased programs;
- ii) Permission be given that during each month the scholar may return home for the duration of one week in order to look after ongoing research programs if so required;
- iii) whenever possible JSPS fellows be given Special highly price-reduced JRL monthly transportation passes in order to increase efficiency of movement.

4.1.3 Submission Date of Reports

In order to be of any assistance to JSPS regarding the submission of recommendations for program improvement, we Foreign Scholars require more time for absorbing all the new impressions which also may require intensive postprogram library studies; and therefore the following is suggested:

- i) instead of the stipulation of providing the final report one month after completion date of mission: 6 months after completion date;
- ii) completion date of program may mean six months after leaving the country in order to complete post-program library and reading studies;
- iii) in general, I found the meticulous handling of overly fixed deadline dates very annoying and counterproductive;
- iv) for Senior Scientists allowances for sudden program changes must be accommodated if those result from national duties of the home base.

4.1.4 Bank Credit Card

I found it next to an absolute insult that I was not allowed to possess a Japanese Bank Credit Card because I was not staying for a period longer than six months. Therefore, I would like to suggest, because without a Credit Card no one can exist nowadays, the following:

- i) every JSPS fellow from abroad coming to Japan even for a period of only one (1) month be made eligible to receive a Bank Credit Card of any of the major Japanese banks;
- ii) the limited banking cards for handling of checking accounts be made bi-lingual (certainly a JSPS-identification card could be very useful!).

4.1.5 Increase of Daily Allowances, Honoraria and Travel/Research Contributions by JSPS

Certainly, the largest number of possible fellowships should be created, but compensation must keep abreast with inflationary cost increases as well as with the Yen devaluation/evaluation. This is a very important issue and should be considered of great urgency. I will summarize my case in stating that if I had to rely only on JSPS resources then I would (as I really did) live on a "graduate student budget" or even less! Under no circumstances would I be able to sustain the support of my wife and definitely not my children to accompany me as much as those would have loved to do!

4.2 PROVISION OF SELECTED READING MATERIAL FOR JSPS SCHOLARS SELECTED FROM ABROAD TO VISIT JAPAN

Although we can obtain a lot of useful material about travel in Japan from JTB, for most of us true scholars very little is provided on serious reading

material on an amateur expert level and only by trail-and-hit method may one be successful in identifying the truly good and reliable up-to-date source material in the English, German, French and/or Russian languages. To my greatest astonishment many of the renowned works were not available in any of the but big bookstores in Tokyo, Osaka or Kyoto and one had to order those with up to six week waiting periods.

Since I want to come very well prepared during my Phase II visit, I request that to me and all other JSPS-fellows a detailed list of pertinent reference material be provided with source of distribution

4.2.1 Bi-lingual Cartographic Maps and Atlases

It is very hard to find good updated bilingual maps and atlases which one ought to have studied carefully in advance:

- i) bilingual road maps;
- ii) bilingual historical maps;
- iii) bilingual geographic maps;
- iv) bilingual atlas (e.g. TEIKOKU's Complete Atlas of Japan).

4.2.2 Basic Textbooks on Japanese Language

Although I was provided with great many simplistic texts on how to acquire a knowledge of the Japanese language, I found that a survey conducted by a team of Japanese experts and overseas scholars would be very useful on this subject matter.

4.2.3 Basic Texts on the Historical Development of Japanese Literature, Music, Philosophy and Religion

Although a great many books are available, I soon found out that the quality and depth varies widely and indeed JSPS could provide an excellent service in identifying the best source books for specific applications.

4.2.4 Bilingual Nature Field Books on Japanese Flora, Fauna, Geology, Oceanography, etc.

It would assist us a lot to find bilingual field books on Japanese flora, fauna, geology, oceanography, etc., which I found to exist in selected fields or sub-fields, however mostly unknown even to the experts. Again, JSPS could provide an excellent service by providing a list of such books.

4.3 IMPROVEMENT OF UNIVERSITY GUEST HOUSE FACILITIES

I found all of the University guest house facilities to be very clean, well groomed and looked after. However, I certainly missed certain important facilities such as

- (i) Electric Washing and Drying Machines: It is very inconvenient to run all over the neighborhood, for example during heavy monsoon rains or take the subway two to three stations to find an operational laundry washing and drying slot machine facility. Note, I did not find a single laundry washing/cleaning business that would accept underwear, socks, wollen pullovers, etc.
- (ii) International Telephone Calling facilities should be installed in all of the University guest houses and/or libraries. I find the telephone paycard (for a fixed number of calls, say 5000 Yens) a great invention and such could be used most favorably. Note, that for visitors from North America or Europe, we must

- usually make calls at off-office hours during the night!
- (iii) Although most guest houses do possess stand-off elevated toilet facilities, some don't; and many office and laboratory buildings don't! For us foreigners of Northern Occidental/American upraising, we are unaccustomed to the use of ground-based sub-surface facilities!

4.4 University Campus Clean-up

With the exception of Waseda University, I found almost all campuses of Japanese Universities to be very untidy, dirty, and uncared for. For a foreign visiting scholar, who was taught at home that the Japanese people are some of the cleanliest, orderliest, it really hurts to see such an awful dirty mess on the campus and in the immediate neighborhood of any campus (including Waseda).

If we cannot instill in our most talented group of upgrowing citizen the drive for cleanliness and quality of the environment, how should we expect the rest of the population to behave!

- (i) Introduce Campus Clean-up Days (one per week);
- (ii) Provide more waste baskets (including receivers for cigarette buds);
- (iii) Keep lavatories and toilets cleaner and provide more western style facilities;
- (iv) make sure that canteen food services are clean (note, I found spoons and cups at times to be very dirty!);
- (v) More attention should be paid to environmental beauty on all campuses. Japan is now wealthy enough to afford the expenditures for campus clean-up and beautification.

4.5 IMPROVEMENT OF ENVIRONMENTAL QUALITY: WATER, LAND, AIR AND HEALTH

Being of German descent and having had to suffer a lot during all of my life in "foreign countries for being a German in origin" and in Germany for being an "Auslandsdeutscher", I feel confident to state that I very well understand how the Japanese people must feel when they are continuously attacked by hostile foreigners because of their selfcenteredness, their cultural, social and religious homogeneity and especially because of their dedication, discipline and industry. I admire the Japanese people, and they more than any other people have currently the most to offer to all nations in enriching man's life and understanding of the universe.

However, the Japanese people have sacrificed a very great lot during the past century, namely environmental quality and may be more (or less) than any other country. This obviously apparent severe problem, yet, has been recognized and the Japanese people indeed are worried about Environmental Quality, but many of their industrial leaders believe enough has been done. I am personally convinced that this is not the case. On the other hand I am convinced that only a highly technologically developed country with highly disciplined and industrial people, such as Japan has to offer, will be able to achieve the long-desired breakthrough everyone is waiting for.

Therefore, I would like to propose to all of my Japanese hosts, colleagues and peers in all walks of life to make "The Quest for Environmental Quality" their first utmost goal which includes over many years to come:

4.5.1 Beautification of Architecture

- (i) beautification of streets, roads and highways;
- (ii) beautification of architecture and removal of ugly post-WWII tin sheds sprawling all over the place;
- (iii) beautification of architectural styles for landscaping, housing etc. in finding a harmonious balance with traditional Japanese styles;
- (iv) beautification of University, Institute and Industry Company building complexes in harmony with traditional Japanese styles.

4.5.2 Quality Control of Air

Although a lot has been achieved over the past decade, still Japan must do much more to improve on the Quality of Air and reduce pollution:

- (i) develop and advance the technology for electro-combustion engine-powered vehicles as a decisive means of cutting down on urban area vehicle exhaust pollution;
- (ii) develop and advance technology for extraction of smoke and poisonous gases from smoke stack exhaust, etc.;
- (iii) introduce core courses at all educational levels (elementary, secondary, high school, college, university) on air quality control.

4.5.3 Quality Control of Water

Although I found many Japanese rivers and waters cleaner than ever before, not only in Japan but the world over must we be very concerned about the maintenance and improvement of the quality of both fresh and sea water:

- (i) improve sewer systems in rural areas;
- (ii) strictly deny permission for the use of gasoline powered motors or any oil releasing vehicles on inland lakes, reservoirs and precious coastal waters;
- (iii) do not permit uncontrolled urban sprawl into valuable farming and natural lands;
- (iv) keep forests and rural areas free of waste materials, especially chemicals, used Cadmium-Nickel batteries, tires, etc.;
- (v) introduce core courses at all educational level (elementary, secondary, high school, college, university) on water quality control.

4.5.4 Quality Control of the Acoustic and Electromagnetic Propagation

Medium

It is a pleasure to understand that Japan has accomplished the most of any industrialized nation in reducing acoustic and electromagnetic radiation noise sources. Yet all of us have not paid sufficient attention to this very serious environmental radiation noise problem.

Although we have all been shocked about the serious aftereffects of the Chernobyl disaster, not to forget Hiroshima and Nagasaki, we yet also need to make the general population know how damaging to nature and the health of living creature any type of acoustic as well as electromagnetic overdoses of radiation really is.

- (i) introduce very strict regulations on radiation level of loud speakers and any other public or inhouse use of acoustic noise/radiation sources which includes modern entertainment music;
- (ii) introduce much stricter industrial codes and standards on radiation level of acoustic and electromagnetic radiation

- equipment of all types used anywhere close to nature and living creatures;
- (iii) develop and advance the technology for planning all transmission line (energy plus communications) systems underground in well shielded ducts;
- (iv) eliminate line of sight microwave radiation links by fibre optical information transmission systems;
- (v) introduce core courses at all levels (elementary, secondary, high school, college, university) on acoustic and electromagnetic radiation quality control.

4.5.5 Quality Control of Health of Living Creatures as a Whole

It is not sufficient that we only be concerned with the quality control of the health of people, but we must be concerned with that of the health of all living creatures otherwise we may be choosing only short-term solution and create much more serious problems for the prolonged existence of the human race and its inhabitants of the terrestrial sphere and the universe.

- (i) introduce more awareness of the value and respect for living creatures as all of our religions East and West alike, are demanding from us!
- (ii) Although I have found some concern about these issues, absolutely no sufficient steps are taken at an overall concerted effort world-wide!
- (iii) introduce courses at all educational levels (elementary, secondary, high school, college, university) on more devotion and religious respect for any creature.

Note, I wish to re-emphasize that I am addressing this specific problem because I am convinced that it only can be the Japanese people who, armored with their science and technology, will be able to provide the leading advances in addressing this problem very realistically.

4.6 CREATION OF AN INTERNATIONAL SYSTEM OF NATIONAL INSTITUTES OF JAPANESE CULTURE AND LANGUAGE

During the post-WWII period and thereafter Japan has attained a very high standard of technological, scientific but also social, linguistic and cultural accomplishments. All of us visitors to your beautiful country and meeting your talented hardworking people know that the Japanese way of life has many positive sides which have a real lot to offer to the entire world and every other nation. For example, here I recall the Goethe Institutes of German Language and Culture, and I am sure that Japan has to offer a lot on a similar scale. Maybe the theme need not be based on one of your famed poets, writers and thinkers, but more on one of your great master of the fine arts, for example of Ukiyo-E, such as Hiroshige or Hokusai.

Certainly, there exist so many reasons why Japan should create such a chain of international cultural institutes and there exist many more reasons why we foreigners should encourage the Japanese people to do so, namely to share with all others the fruits of the hard labor for the hard-fought advances in the sciences, the arts and technologies which ultimately lead to the enrichment of culture.

Thus, may I suggest for consideration:

- (i) the Japanese people create for the benefit of their own and foreign people an international chain of national Japanese institutes of culture;

- (ii) provide lectures, seminars, short courses, performance examinations on Japanese language, literature, art, fauna, flora, geology, sociology, etc.;
- (iii) invite future JSPS fellow awardees to participate in a six week to three month cultural accommodation program (similar to one by the Goethe Institute, for example);
- (iv) provide a national workshop for gathering once or twice a year for all JSPS fellows, who are carrying out their tenure during that period in Japan;
- (v) create a JSPS newsletter for program continuation and updates to be distributed to all former JSPS fellow awardees;
- (vi) hold weekly open houses at JSPS headquarters or the desired cultural centers for increased interaction of current JSPS fellows with Japanese scholars and scientists;
- (vii) finally, once a year, we JSPS fellow awardees from abroad should be invited to meet with the dignitaries of the Japanese government and society.

V ACKNOWLEDGEMENTS

In concluding this report, I first wish to beg understanding for the delayed submission of this FINAL REPORT according to JSPS stipulations. However, I found that next to all the other duties of a day-by-day sixteen-hour work day, I would never have been able to accomplish it even a day earlier. Indeed, I will require many additional weeks and months to rework the entire report which thus can only be considered a FIRST DRAFT of what is to become a FINAL REPORT in the future.

Particularly, I must beg the pardon of Professor Kyohei Fujimoto for my continuous delaying of deadline dates and revamping of schedules. May the sincerity and many hours I have put into the preparation of this report convince him, however, that I am not going to let him down. On the contrary, I should thank him foremost as a friend, a competent and wise colleague, and a very innovative researcher for all the advice and encouragement plus angry pushes he has given me to have this report finally done.

The interaction among my four hosts, Profs. Kyohei Fujimoto, Yasumitsu Miyazaki, Takeo Yoshino, Lin Shi-Ming and myself was excellent and I want to express my sincerest thanks to them for their hospitality and generosity, and for opening so many doors wide for me to become a lasting friend of the Japanese and Chinese people. It was Professor Takeo Yoshino, who showed me how beautiful the hidden corners, not commonly accessible to tourists, are and that Japan and its sphere of life can only be comprehended from a study of its integrated geology, geography and ecology from which its island character is derived.

At all of the three host universities in Japan and those in Xian, I was offered to stay at their unique guest facilities which I enjoyed and I was very grateful for. Thus, I wish to take this opportunity and express my sincere gratitude to the senior administrators, Vice Presidents and Presidents who offered me the use of these useful facilities.

Also, I would like to thank Mrs. Yuko Furukawa of the JSPS Administration Office in the Yamato Building of Chiyoda-ku for her harmonious collaboration and understanding of the many special issues I had to put forth in my case.

Similarly, I would like to thank all of the administrators of the other organizations who with their devoted and enthusiastic collaboration made these cultural and research travels possible including Prof. Haung Zhong-zheng, Dr. George B. Wright, Dr. Annette M. Johnke, my department head, Prof. Wai-Kai Chen and my deans, Dr. Paul M. Chung, and Dr. Ronald P. Legon of the University of Illinois at Chicago. In addition, I would like to thank my research contract scientists and monitors Drs. Kenneth Davis, Arthur K. Jordan, Michael Morgan, Richard G. Brandt, ONR; Drs. Robert J. Dinger, Guenter Winkler, Brett Borden, NWC; Drs. Otto Kessler, Raymond Dalton, NADC; Drs. James W. Mink, Walter Flood, ARO; and Drs. Fred Sedenquist, Robert J. Russel, Lloyd W. Root, MI-LAB, for their interest in our research collaboration.

Finally, I wish to thank my family and in particular my dear and brave wife, Eileen-Annette, for enduring the many hours I have spent away from home, and for being so accommodating during the struggles of having the FINAL REPORT prepared, edited and typed. I also thank my capable graduate research assistants, Matthias Walther, Jonas Okeke, Thomas Foo, and Amit Agrawal, for sharing into typing of the manuscript, and visiting Professors Masakazu Sengoku, Mitsuru Tanaka and Zha, Qiong-Zheng for proof-reading and discussing the text.

REPORT ON SABBATICAL RESEARCH LEAVE

(1988 MAY 31)

By: Wolfgang-M. Boerner, Professor & Director
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Title: THE ADVANCEMENT OF INVERSE METHODS IN HIGH RESOLUTION POLARIMETRIC
TARGET IMAGING IN AN AIR/LAND/SEA CLUTTER ENVIRONMENT

Period: WQ/SQ 86-87: 1987 Jan. 01 - 1987 July 31

- Sponsors:
- (1) The University of Illinois at Chicago, Engineering College, EECS
(WQ/SQ 86-87)/Sabbatical Leave for Two Quarters at Full Salary.
 - (2) Alexander von Humboldt Stiftung, Bonn-Bad Godesberg, FRG- West
Germany/US Senior Scientist A. von Humboldt Fellow Award.
 - (3) Royal Norwegian Council for Scientific & Industrial Research,
Environmental Science Technology Program; Kjeller, Norway/US
Senior Scientist NINF Fellow Award.
 - (4) NATO-AGARD Distinguished Lecturer Program, ONERA, Chatillon-
Bagneux, France/Distinguished Lecturer Award.

- Hosts:
- (1) The German Aerospace Research & Test Establishment, DFVLR-NE-HF,
Oberpfaffenhofen, D-8031 OPH/Post Wessling, Obb., FRG - West Germany.
Attn: Dr. Wolfgang Keydel, Director, +[49]8152-28-306
 - (2) The Royal Norwegian Council of Scientific & Industrial Research,
Environmental Science Technology Program, NINF-PFM, Boks 25/Forsk
Inst. N-2007 Kjeller, Norway.
Attn: Dr. Dag T. Gjessing, Director, +[47]6-80-70-90/93
 - (3) Organization National Etude Recherche Aerospatiale, Systems Radar
29 Ave de la Division Le Clerc, F-92-320 Chatillon-Bagneux
Attn: Dr. Jacques Dorey, Director, +[33]146-57.11.60

Schedule: Due to the strong research contract and collaborative research involvement in the USA, the NW Pacific Orient, and in NATO-Europe, a tight travel schedule was adopted. During these seven months, five return flights to the USA had to be incorporated in order to participate in ongoing contract reviews and negotiations. During my stay in Europe, I travelled about 30,000 km by the BMW-535 Dienstwagen made available through the A. von Humboldt award, and another 15,000 km by train (during the tough winter months 1987 Jan.-March) and airplane (from Noordkap to Lisbon, from Weston-Super-Mare to Linköping). More than 200 hours in lecture/seminar presentations during invited NATO/ESA/CCG/ NINF/DFVLR/University/National Research Institutes had to be included in this schedule next to extensive research discussions, consultations and interactions.

Phase I: 1987, Jan. 01 - Feb. 07

Jan. 01 - 08: Travel preparations and contract debriefings
(CHI/WA/HUN/CHI) including visits of ONR,
Arlington, VA; NRL, Washington; APL, Laurel,
MD; DARPA, Arlington; MICOM, Huntsville, AL.

Flight: LH 431: CHI (87-01-09-16:30)-MUN (87-01-10-9:34)

Jan. 09 - Feb. 07:

Research Interaction Period I

I-1

Interactions with:

DFVLR-OPH

UEN-ERLANGEN (NATO-ARW-DIMRP 88)

FGAN-WW

AEG-ULM

SEL-STU

I-2

Attendance of 1987 International URSI, Comm. F, MSRS Symposium, Göteborg, Chalmers University of Technology, 1987 Jan. 19 -22, Palmstedtsalen.

I-3

Presentation as invited monthly colloquium speaker at University of Bremen & Alfred Wegener Institut für Polarforschung, Bremerhaven, 1987 Feb. 2 - 4: "Anwendung elektromagnetischer inverser Streungsmethoden in der Radar-Erd-Fern-Erkundung."

Flight: LH 430: MUN (1987-02-07-12:35)- CHI (1987-02-07-17:14)

Phase II: 1987, Feb. 08 - March 15

Feb. 08 - Feb. 17:

Travel debriefing/contract monitoring meetings/contract debriefing (CHI-HUN-WA-CHI)

Flight: LH 431: (CHI: 1987-02-18-16:30)- MUN (1987-02-19-9:34)

Feb. 18- March 15:

Research Interaction Period II

II-1

Interactions with:

DFVLR-OPH

UEN-ERL

TUD-DARM

TUK-KARL

DIEHL-NGB

AEG-ULM

FGAN-TÜB

ZEISS-KOCH

II-2

Invited keynote speaker at Wehrtechnische Seminare: Multisensorik unter Einbeziehung der Bionik, 1987 Feb. 19-21, Bonn. W-M. Boerner: Polarimetric Imaging in Nature, Science & Technology.

II-3

Visit (1987 Feb. 24-25) of Fundamentalstation WETTZELL, Satellitenbeobachtungsstation: Satelliten-Geodäsie-VLBI-Experimente, D-8493 Kotzting, Bayerischer Wald
Attn: Dr. Wolfgang Schlüter, Director
+[49]9941-8643

II-4

Participation in calibration measurements at NTNF-PFM, Kjeller, Norway, March 10 - 12.
(Drs. Dag T. Gjessing, Jens Hjelmstad/NTNF;
Drs. Robert Turner, John Apel and Bob McDonough/APL)

II-5

XV Annual Symposium for Humboldt Awardees in
Rottach - Egern/Tegennsee, March 12 - 14.
(Main speaker: Georg Hendrick von Wright:
Science & Rationality)

Flight: LH 430: MUN (1987-03-15-12:35)- CHI (1987-03-15-17:14)

Phase III: 1987, March 16 - April 17

March 16 - March 21: Travel debriefing/contract
monitoring/debriefing (CHI-SAN
DIEGO-ALAMOGORDO-CHI)

Flight: LH 431: CHI (1987-03-22-16:20)- MUN (1987-03-23-9:34)

March 22 - April 17: Research Interaction Period III

III-1 Interactions with:
DFVLR-OPH
DFVLR-PORZ/WAHN
BMFT/BMVtg, Bonn
NATO Hqts.
AWL-Portsmouth
THORN-EMI, Wells
RSRE-GR. MALVERN
ONR, London
SHAPE-TC Scheveningen
TNO-Den Haag
MBB- Mu - Ottobrunn

III-2 Attendance of International Conference on
Antennas & Propagation, ICAP '87, York,
England, UK, 1987 March 29 - April 02;
presentation of two invited papers:
W-M. Boerner, The Electromagnetic Inverse
: Problem Current State of the Art
W-M. Boerner, Recent Advances in Radar
Polarimetry: Assessment of the State of the
Art

III-3 Extensive discussions (87 April 03) at
ONR-European Branch Office, 223 Old
Marylebone Rd., London, NW 1-5th,
+[44]-1-409-4479. Attn: Dr. David L. Venezky,
Scientific Director

III-4 Visit of American Embassy with Federal
Republic of Germany, Deichmann's Aue 29, D-53
Bonn 1-Mehlem +[49]228-339-1. Scientific
Attaché: Dr. Edward H. Malloy: Discussions on
improving exchange programs for US scientists.

Flight: LH 432: MUN (1987-04-17-11:40)- CHI (1987-04-17-14:20)

PHASE IV: 1987, April 18 - June 7

April 18 - April 23: Travel debriefing/contract monitoring/contract
debriefing (CHI-WA-HUN-CHI)

Flight: AM 88: CHI (1987-04-24-4:15)- MUN (1987-04-25-9:30)

April 24 -- June 7:

IV-1

Research Interaction Period IV

Interactions with:

DFVLR-OPH

ONERA, Paris

BWH, Hamburg

MPI, Hamburg

NTNF-PFM, Oslo

FOA-III, Linköpping

IV-2

Invitation to Universität Bern, Applied Physics Institute, Bern, Switzerland: Prof. Erwin Schanda (1987 April 28 - 30). Swiss Federal Department of Defense, Rüstungsamt/FA 96 (Radar & EKF)

IV-3

NATO-AGARD Workshop Short Course Lecture Series: "Advanced Radar Polarimetry, Radar Cross Section Matrix Measurements, and Radar Absorbing Material" (Distinguished Lecturer: Dr. Wolfgang-M. Boerner, Prof. UIC, 1987 May 03 - May 08. (see attachment)

IV-4, May 12

Invited monthly lecturer at Gesamthochschule Kassel, Institut für Theor. Electrotechnik, Prof. Karl-Jörg Langenberg) Wilhelmshöher Allee 71, D-3500 Kassel +[49]561-804-64-68 "Inverse Methods in Electromagnetic Imaging"

IV-5, May 13

Invited monthly lecturer at the Max Planck Institut für Meteorologie; Universität Hamburg, Prof. Helmut Jeske, "Polarimetric Doppler Radar Meteorology"

IV-6

Research interaction with NTNF-PFM, Kjeller/Tromsø, Langesund, Norway: 1987 May 15 - May 30: (i) Participation in polarimetric scatterometer measurement campaign at Langesund; (ii) Research interactions at Tromsø, Trondheim; (iii) Visit of EU-SCAT; (iv) Visit of NIT, Trondheim; (v) Interaction with MIROS. (Profs. Dag T. Gjessing, Asgeir Brekke, Andreas Toning; Drs. Jens Hjelmstad, Helge Nareid, Ove Bratteng; Mr. Dagfinn Leivulfsrud)

IV-7

Visit of Karl von Linné Botanic Garden, Uppsala, May 31

IV-8

Visit of FOA3/36 Radar Imaging Division, Linköpping, Sweden, June 01

IV-9

Invited monthly lecturer at Bundeswehr Hochschule Hamburg, Division Electronics and Radar (Profs. Dr-Ing. Kurt Nixdorff and Dr-Ing. Hans G. Wässerling) "Polarimetric Radar Techniques in Target Allocation and Detection", June 02

IV-10

Invited monthly lecturer at Bundeswehrhochschule München, Division Electronics and Remote Sensing (Prof. Dr-Ing.

Gerhard Flachenecker) "Inverse Methods in
Radar Polarimetry", June 04

Flight: AM 89B: MUN (1987-06-07-12:25)- CHI (1987-06-07-17:00)

Phase V/VI: 1987, June 08 - July 31

June 08 - June 14: Travel Debriefing/Contract Monitoring/
Debriefing (CHI-URBANA-HUN-CHI)

Flight: LH 431M: CHI (1987-06-14-16:20)- MUN (1987-06-15-7:50)

June 15 - July 15: Phase V: Cultural/scientific research round
trip with wife and children: München --
Stuttgart - Heidelberg - Kaiserslautern - Metz
- Verdun - Reims - Orleans - Blois - Ambois -
Chartres - Paris - Giverney - Lille -
Portsmouth - Salisbury - Stonehenge - Wells -
Bath - Bristol - Rhaiden - BulthWells -
Leominster - Warwick - Oxford - Richmond (Kew
Botanic Gardens) - London - Canterbury - Dover
- Ostende - Vlissingen - Rotterdam - Hilversum
- Hooze Vale - Arnheim - Gelsenkirchen -
Bochum - Kassel - Bad Hersfeld - Eisenach -
Weimar/Erfurt - Karl Marx Stadt (Chemnitz) -
Radebeul - Bautzen - Dresden - Leipzig - Halle
- Plauen - Hof - Bayreuth - Erlangen -
Münchberg - Neuendettelsau - Weissenburg -
München.

Phase VI : 1987, July 16 - July 31

July 16 - July 28: Final Phase of research interaction with
DFVLR-OPH
DFVLR-PORZ (Head Quarters)
UEN-ERL
TUM-MUN
AEG-ULM

Flight: LH 432M: MUN (1987-07-28-11:40)- CHI 1987-07-28-14:20)

July 29 - 31: Completion of sabbatical research leave:
travel debriefing at UIC.

Summary

The research conducted during my sabbatical research leave was primarily conducted within the premises of the German Aerospace Research and Test Facility DFVLR-Oberpfaffenhofen in collaboration with its Remote Sensing Sciences & Technology Division, Electromagnetic Scattering and Imaging, and Polarimetric Radar Sections. One of the prime goals was to provide further guidance and consultation for the use of the C-Band Dual Polarization Doppler Radar Research Facility and its implementation in polarimetric doppler radar rain scatter analyses in collaboration with the DFVLR, Division of the Physics of the Atmosphere.

In addition, in close collaboration with DFVLR, two research site visits were carried out: (1) to the Norwegian Council of Scientific & Industrial Research, Environmental Surveillance Program NTNF-PFM-Kjeller, where at Langesund extensive measurement campaigns on polarimetric scatterometer backscatter from rough ocean surfaces with and without distinct ship/submersible wake interference were executed; (2) to the French Department of Defense,

Organisation Nationale Etude Recherche Aerospatiale, ONERA, Chatillon-Bagneux, where at Rennes extensive broadband polarimetric scattering matrix radar analyses of complex radar targets were in progress. In addition, major visits (upon invitation), in context with these polarimetric radar research studies were conducted with (i) the Alfred Wegener Institute for Polar Research, Polar Meteorology Division for implementation of polarimetric doppler radars in polar ice storm analyses; (ii) the University of Bern, Applied Physics Department, Remote Sensing Laboratory, carrying out measurements on the determination of polarimetric RCS signatures of vegetation (plants, crops, trees, shrubs, algae, etc.); (iii) the Swedish Defense Research Establishment, Radar Division, FOA ITT-Linköping for the analysis of polarimetric ship/submersible wake signatures in the Bothnian Bay at shallow waters; (iv) the Royal Signals and Radar Establishment, Great Malvern, Radar Signatures Division for the assessment of polarimetric doppler radar signature implementation in tactical radar; (v) the Supreme Headquarters of the Allied Powers in Europe, Technical Center at SHAPE-TC, Scheveningen/Den Haag for experimental and data processing analyses of polarimetric scattering matrix radar data; (vi) the Dutch Organization for Applied Sciences, Physics & Electronics Laboratory, TNO-PEL, Schevening for the analyses of polarimetric sea scatter signatures with/without naval targets; and (vii) visits to at least twelve industrial RDE centers (AEG, MBB, DIEHL, SEL, SIEMENS, ZEISS, DORNIER, THORN-EMI, ERICSON, SELENIA, MATRA, TOMPSON-CSF, AEROSPATIALE, etc.) engaged in polarimetric radar development. As a result of these extensive interactions, five major research papers have resulted, in addition, to one major NATO Advanced Research Workshop on Direct and Inverse Methods in Radar Polarimetry to be staged in Bad Windsheim, FRG, 1988 Sept. 18 - 24, during the second phase of the A. von Humboldt Award tenure (1988 Aug. 15 - October 15).

In conclusion, my research interactions with scientists, engineers, and environmentalists from within NATO Europe, Sweden and Switzerland, engaged in the remote sensing of the terrestrial environment by implementing polarimetric doppler radar/SAR imaging methods were exhaustive, extensive, fruitful and very successful. We have made many new research contacts, coordinated and streamlined research and developmental efforts in the advancement of polarimetric radar technology. Paired with my collateralized research efforts in the Pacific NW Orient, which included Japan, Taiwan, S. Korea and the People's Republic of China, Austral-Asia (NZ+Austr.), and the United States and Canada, we have now assembled the major research teams in this novel important discipline of Polarimetric Radar/SAR/ISAR Remote Sensing which will be gathering again during:

- (1) The 1988 IEEE-APS/URSI-USNC International Symposium, Syracuse, N.Y., 1988 June 6 - 10. (six major sessions organized by W-M. Boerner and devoted to polarimetric radar analyses, scattering and remote sensing.
- (2) The Third Polarimetric Radar Technology Workshop, at the Wernherr von Braun Rocket Auditorium, Redstone Arsenal, AL 1988, August 16 - 18 (W-M. Boerner: Co-Chairman/Proceedings Editor)
- (3) The NATO-ARW-DIMRP 88, KUK Hotel Residenz, Bad Windsheim, FRG, 1988 Sept. 18 - 24 (W-M. Boerner: Director/Proceedings Editor)
- (4) The CCG Short Course Lecture Series on Polarimetric Radar Technology, DFVLR-Oberpfaffenhofen, 1988, Sept. 26 - 29 (W-M. Boerner: Main Lecturer/Workshop Chairman)

Expansion of Research Collaboration

The research collaboration between DFVLR, NTNF, ONERA and UIC-EECS/CL has been expanding favorably leading to various counter visits and coordinated research

efforts, sponsored in part by the US Defense Advanced Research Project Agency and the US Office of Naval Technology. Especially our POL-SAR ship and submersable wake detection projects are well advancing, also involving TNO, RSRE and FOA III. All of these research groups will be strongly represented during the above mentioned Polarimetric Research Workshops.

As a result of my inter-European and inter-NW Pacific oriental research inter-actions rather strong multi-national research collaborative consortiums dealing with Polarimetric Radar Studies are emerging. At last, we have been able to close the gap between NATO-European/North American and NW Pacific Allied Research laboratories and due to my personal contacts many strong active research collaborative programs have been established.

Phase II Continuation of A.v.H./NTNF/ONERA Interaction

The Phase II interaction will take place during 1988 August 15- Oct. 15, including one major measurement campaign sponsored by US-DARPA, US-ONT, UK-MOD, FRG-BMVTg, No-MOD and NATO, for POL-SAR/POL-RAD wake detection at moderately rough seas in the North Sea off the Norwegian Coast, and three workshops.

Publications

Several publications are currently being prepared in collaboration with research staff of DFVLR, RSRE, NTNF, FOA III and UIC-EECS/CL which will be included in the Proceedings of the NATO-ARW-DIMRP'88 and of the Third Polarimetric Radar Technology Workshops'88.

Attachments

A.1 Program Descriptions:

- (1) DFVLR
- (2) NTNF
- (3) ONERA

A.2 Polarimetric Workshop/Symposium Schedules:

- (1) NATO-ARW-DIMRP'88
- (2) Third Polarimetric Radar Technology Workshop
- (3) CCG Short Course on Polarimetric Radar Theory & Technology.

A.3 Coordination of NW-Pacific Orient International Symposia, Workshops and Expert Retreats

- (1) ISAP'89, Tokyo, Aug. 22-25
- (2) ISAS'89, Shanghai, Aug. 19 - Sept.01
- (3) ISEC'89, Nagoya, Sept. 8-10
- (4) ISNCR'89, Kyoto, Nov. 14-16

A.4 Updated Curriculum Vitae: W-M. Boerner (Short Form)

THE JSPS FELLOWSHIP FOR RESEARCH
IN JAPAN

RESEARCH REPORT

Date 1988 May 31

Reported by: BOERNER, Wolfgang - Martin, Prof. Dr.

Host Scientist: Fujimoto, Kyohei, Prof. Dr.

Research Period: From 1988, March 14 To 1988, April 30

Title of Research in Japan: PHASE II: Advancement of Science & Technology
in High Resolution Radar Polarimetry
Using Electromagnetic Inverse Methods

(Signature) Wolfgang-M. Boerner
Dr. Wolfgang-M. Boerner



THE
UNIVERSITY
OF
ILLINOIS
AT
CHICAGO

Communications Laboratory (M/C 154)
Department of Electrical Engineering and Computer Science
4210-4211 Science and Engineering Laboratories
Box 4348, Chicago, Illinois 60680 U.S.A.
(312) 998-5460/5140

June 15, 1988

Professor Dr. Kyohei Fujimoto
Dept. of Applied Physics
Tsukuba University
Bldg. 3F, Rm. 627
Tsukuba-Shi, Ibaraki-Ken
305 Japan
+(81) 298-53-5313/2435

Dear Kyohei:

It was a pleasure to meet again with Prof. Kazuhiro Hirasawa and so many Japanese colleagues during the 88 IEEE-APS/URSI-USNC Symposium in Syracuse and then, thereafter, having Dr. Hirasawa and many others visiting us in Chicago. I had intended to complete my JSPS (Final) Phase II Report before his departure which was then not possible due to the unexpected high number of Chinese, Japanese, and European visitors.

Today, I am enclosing the original and one copy of the final report and one copy each to Mrs. Yuko Furukawa, Profs. Yasumitsu Miyazaki, Takeo Yoshino, Toshio Sekiguchi, Takeo Abe and to my personal friends, Mr. Masami Iwasaki and Mr. Takao Namiki. Again, I wish to express my sincerest gratitude for your pleasant and stimulating hostship and your personal friendship.

In the meantime, Dr. Yoshio Yamaguchi, who is being jointly sponsored by Monbusyo and UIC-EECS/CL, has arrived and settled to collaborate with us for one year.

Looking forward to meeting you soon again.

Sincerely yours,

Wolfgang-M. Boerner

Wolfgang-M. Boerner, Ph.D.
Professor & Director

Enclosures

cc: Mrs. Yuko Furukawa
Prof. Yasumitsu Miyazaki
Prof. Takeo Yoshino
Prof. Toshio Sekiguchi
Prof. Takeo Abe
Mr. Masami Iwasaki
Mr. Takao Namiki
Prof. Wai-Kai Chen
Prof. Philip L. Hawley
Prof. Susan V. Lourenco

RESEARCH REPORT
(1988 MAY 31)

THE JSPS FELLOWSHIP FOR RESEARCH IN JAPAN

Prepared by: Dr. Wolfgang-M. Boerner
(JSPS Fellow) Professor & Director
UIC-EECS/CL (M/C 154)
840 W. Taylor St. SE1-4210
Chicago, IL/USA 60680-4348
+1(312)-996-5480/5140

Title: Advancement of Science & Technology
in High Resolution Radar Polarimetry
Using Electromagnetic Inverse Methods

Program Phasing: The research collaboration of this JSPS Fellow with his three Japanese Host Scientists is spread over many years and separated into three major phases. Here, we are reporting on the RESULTS of the Second Phase which was subdivided into five parts including a visit to Xidian Daxue, Xian, China for current and future enrichment of the program.

Duration: PHASE II: 1988 March 14 - 1988 April 30
Ph.II, Pt.1: March 15-26/TUS: Prof. Kohei Fujimoto
Ph.II, Pt.2: March 27-April 3/UEC: Prof. T. Yoshino
Ph.II, Pt.3: April 3-9/TUT: Profs. Y. Miyazaki & T. Abe
Ph.II, Pt.4: April 10-14/TUS: Prof. Kyohei Fujimoto
Ph.II, Pt.5: 1988, April 15-30/Xidian Daxue, Xian: Prof. Mao, Yu-Kuan and Ge, De-Biao; NPU, Xian: Prof. Lin, Shi-Ming

Host/Inst: Prof. Kyohei Fujimoto, Tsukuba University of Science
Tsukuba Kagaku Daigaku, Inst. of Applied Physics
Tsukuba-Shi, Ibaraki-Ken 305, Tel 81-298-53-2435/5313

Collaborating Institutes:

Co-Host Inst: TUT
Toyohashi Gijutsu
Kagaku Daigaku
Tempaku-cho, Toyohashi 440
81-532-47-0111x528/574

Co-Host Inst: UEC
Denki Tsushin
Daigaku
Chofu-shi, Tokyo 182
81-424-832161x3351

Co-Host Inst: Xidian Daxue,
Tai-Bai Lu 2
Xian, Shaanxi, China
86-29-55801

Summary: My Phase II (1988 March 14 to April 30) in continuation of my Phase I (1986, March 23 to July 23) engagement as a JSPS Fellow from the USA in Japan was again a most rewarding experience due to the very dedicated attention given to me by my Japanese hosts who opened up so many academic, scientific, cultural, social and religious windows for me to become an everlasting friend of the Japanese people, a sound admirer of their multivaried accomplishments and a fellow-struggler for the beautification of their cities and the improvement of their rich marine/coastal/land/mountain islands environment. Although this second phase has been a rather short visit by number of weeks and days, it was a most efficient and rewarding time thanks to the well groomed Japanese punctuality, correctness, preciseness and dedication of getting things done at the best of one's abilities. My three previous hosts and my new host, Prof. Takeo Abe, Niigata University, all four so different in character, scientific approach and scope; who are highly talented and innovative, with unique personal interests and hobbies, made it possible, because of their rather striking different approach to academic and research guidance, for me to obtain a rather

rare glimpse behind the curtains of strict formality which so much can obscure a real vision of Japan. I was able to observe a lot, to deliver many lectures, to return with many new ideas and, above all, with the confidence of having made many new long lasting friendships out of which productive research innovation will result.

Before concluding with this executive summary, I wish to emphasize the importance of visiting both Japan and the Oriental Continent (Korea, China, Taiwan) whenever, we "occidentals" visit the Orient in order to obtain a deeper appreciation of the diversification but also, unique similarities of these countries; and thus I was very grateful that a short visit to the Universities of Xian, and particularly during Phase II of Xidian Daxue, was approved by JSPS to be included in my research travel program.

This Phase II (Final) Research Report is short and complements my Phase I Report of 1986 August 15. All previous comments and suggestions still apply, some of which have been further amplified. Specifically, this Phase II (Final) Research Report contains in: Chpt. II-1: The Itinerary, Chpt. II-2: A Summary of Academic Activities; Chpt. II-3: Major Observations; Chpt. II-4: Suggestions for Improvement. Chpt. II-5: Summary of P.R. China Travel; and Chpt. II-6, Acknowledgements.

CHAPTER II-1: THE ITINERARY

Phase II: 1988 March 14 - April 30

Phase II: Pt. 1 (1988, March 17-26): Tokyo, Tsukuba

UIC-Preparations/Debriefing: 1988, March 14-16

Travel (UA 097/097: CHI-LA-NAR): 1988, March 16-17

1988, March 18: Visit to ONR Far-East Branch Office
Akasaka Press Center, Roppongi
JSPS, Yamato Bldg.
Chiyoda-Ku

Invitation by Mr. & Mrs. Masami Iwasaki and Mr. & Mrs. Takao Namiki, Takashima, Nihonbashi

1988, March 19/20: Tokyo Cultural Centers (Ueno Park National Galleries & Museums and Ohda Ukiyo-e Museums, Shibuya)

1988, March 20: Invitation by Prof. & Mrs. Kyohei Fujimoto, Sakura-Mura

1988, March 21-26: Tsukuba Daigaku

Research Discussions with Prof. Kyohei Fujimoto and Kazuhiro Hirasawa and collaboration with staff and graduate research students (Dr. Simeon Voynov, Visiting Scientist Sofia, Bulgaria; Dr. Zhang, Yi-Min, Visiting Scholar P.R. China; Prof. Tohru Idogawa)

1988, March 26: Visit to: Doboku Kenkyo Jo (Public Works Research Institute, Ministry of Construction), Water Resources & Flood Control Department, Asahi Toyo-Sato-Machi, Tsukuba-Shi:
Dr. Fumio Yoshino
Dr. Hirashi Hashimoto
(Discussions about DND Dual Polarization (Niju Hempa)
Doppler Radar Rain Analyses: Invitation to NATO-ARW-DIMRP, 88)

Phase II: Pt. 2 (1988, March 27- April 2): Tokyo Kogyo Daigaku, Denki Tsu-Shin Daigaku/Sugadaira

- 1988 March 27: Invitation by Prof. & Mrs. Kazuhiro Hirasawa, Setagaya-Ku
- 1988, March 28: Visits of Tokyo University and Tokyo Institute of Technology
- 1988 March 29: Preparation for Instrumentation Check-up of EXOS-D/GEO-TAIL I Satellite:Denki Tsushin Daigaku: Profs. Takeo Yoshino and Isamu Nagano (Kanazawa Univ.)
- Afternoon/Evening: Japan EIC Meeting: Takadano-baba, Waseda University Campus (Heian-Kaku Bldg.): Interaction with Japanese colleagues specializing in electromagnetic wave propagation, diffraction, scattering and remote sensing (Prof. Kiyohiko Itoh, Hakkaido Daigaku; Prof. Masahiro Suzuki, Hokkaido Inst. of Technology; Profs. Tosiyo Koga, Takashi Takenaka, Kyushu Daigaku; Profs. Takeo Abe and Masakazu Sengoku, Niigata Univ.; Prof. Mitsuro Tanaka, Oita Daigaku; Prof. Saburo Adachi, Tohoku Daigaku; Prof. Bandhit Rojarayanont, Chulalongkorn/Thailand; etc.)
- 1988, March 30: Denki Tsushin Daigaku (Profs. Takeo Yoshino, Tsutomu Suzuki, Dr. Takashi Shibata)
- Visits of RRL (Dem-pa-ken): changed to Communications Research Lab. (Tsushin Sogo Kenkyu-Jo): Drs. Tomohiro Oguchi, Ken-Ichi Okamoto and Jiun Akawa: Discussion about Dual Polarization Doppler Radar Rain Scatter Analyses.
- 1988, March 30-
April 02: Visit of Sugadaira Uchu Dempa Kan-Soku-Jo (Space Wave Observatory) Prof. Takeo Yoshino and Mr. Ichihiro Tomizawa: Discussion about earthquake electromagnetic precursor emission/radiation detection and monitoring.
- 1988, April 03: Visit to Gerd Knäpper, (recipient of the Prime Minister's Award), with Dr. Masao Gotoh and Mr. Kazuo Morinaga at the Tarosaka Yake Studios, Daigo-Machi, Kuji-Gun, Ibaraki-Ken: Discussion about international ceramic and potteryware development of 1970-1980's.

Phase II: Pt. 3 (1988, April 3-April 9): Visits of Tokyo, Toyohashi; Nagoya, Toyama, Niigata

- 1988, April 4: Tsukuba Univ. (Profs. Kyohei Fujimoto, Kazuhiro Hirasawa and Fumio Uchiyama)
- 1988, April 5: Visit of Nihon Univ./Chiba Campus (initiation of contacts with Prof. Yozomu Hasebe)
- Evening: Meeting of Kuramae Kogyo Kaikan with Prof. Toshio Sekiguchi and his former students, Drs. Ken-Ichi Kagoshima, Kyoji Murakami and Bandjit Rojarayanont: general discussions about lecture methods on electromagnetic scattering and remote sensing theory; and structuring of modern EECS curriculae.
- 1988, April 6: Visit of Toyohashi Gijitsu Kagaku Daigaku, Joho Kagaku Department: Prof. Yasumitsu Miyazaki, staff (Dr. Mitsuo Yamaga, Mr. Haruo Miyawaki) and students.
- Visit of JEMCO, Japan EMC consulting office, Toyo-Hashi-Shi, Aichi-ken (Mr. Hiroshi Miyazaki)
- Visit of Nagoya Univ., Dept. of Earth Sciences, Chikyu Kagaku: Profs. Hitoshi Mizutani and Isao Yamada: electromagnetic radiation emission phenomena during rock-fracture at extremely high pressures: relationships between electromagnetic, piezo-electric and rock-fracture emission phenomena and applications to earthquake precursor radiation phenomena.

Invitation by Prof. & Mrs. Yasumitsu Migazaki, Minami-ku/
Nagoya

- 1988, April 7: Visits of Gifu Univ., Takayama, Kamioka and Toyama.
Inspection of Doboku Kenkyo-Jo, Dual Polarization Doppler
Radar Facility at Toyama flood control/weather forecasting
research center (Mr. Masamitsu Mizuno, Dr. Fumio Yoshino, Mr.
Seiji Asai)
- 1988, April 8/9: Visit and Research Seminar Presentation at Niigata Daigaku,
Engineering Faculty (hosts: Profs. Takeo Abe, Masakuzo
Sengoku, Yoshio Yamaguchi and Hideo Makino)
Preparation of Dr. Yoshio Yamaguchi & family's one-year visit
to UIC-EECS/CL (1988, June 14 - 1989, June 13)
- 1988, April 9: Visit of the ITO Mansion, the HYO-KO Migrating Bird Refuge
and the Niigata War Memorial & Beach Botanic Garden with Dr.
Yoshio Yamaguchi.
Invitation at Yubin-Chokin-Kaikan by Dean Takeo Abe

Phase II: Pt. 4 (1988, April 10- April 14) Tsukuba, Tokyo, Yokohama

- 1988 April 10: Last extensive visit of Tsukuba Botanical Garden during PhII.
Visits of Johnan Dairy Farming Coops with veterinarian Dr.
Masao Gotoh in the vicinity of Tsukuba-San.
- 1988, April 11: Discussions with Prof. Kyohei Fujimoto and Kazuhiro Hirasawa:
Future research program interactions.
Discussions with Prof. Kasuke Takahashi, Physics Div.,
National Lab. for High Energy Physics, Oho, Tsukuba:
Preparation of visit by former UIC student Dr. James B. Cole
to Kamioka Neutrino Observatory of KEK.
Invitation by Prof. K. Fujimoto and K. Hirasawa : Departure
and Closing down of Phase II interactions. Preparation of
visits of Profs. Hirasawa and Fujimoto to UIC during 1988-89.
- 1988, April 12: Visit of ISAS, Uchu Kagaku Kenkyu-Jo, Sagamihara: Dr. Haruto
Hirasawa: discussions about dual polarization SAR remote
sensing data interpretation
Visit of Tokyo Kogyo Daigaku, Nagatsuda-Suzukakedei Campus:
Prof. Matsuo Sekine, (Prof. Toshimitsu Musha), Dr. He, Bin:
Discussion on Weil-Bull distribution function analysis of
polarimetric doppler radar data.
- 1988, April 13: Visit of Furukawa Electric Co., Yokohama R&D Lab. (Mr. Masami
Iwasaki, Mr. Toshiaki Shibata, Dr. Kenji Shinozaki, Mr.
Hisaharu Yamagawa): Introduction on recent advances of
optical communication fibre manufacture and applications;
electro-optical device technology, etc..
Invitation by Mr. Masami Iwasaki to Furukawa Denko Guest
House.
- 1988, April 14: Visit of ONR-Far East Branch Office and JSPS Offices
Transfer to Narita Airport. (UA-897: TOK-NAR-SHAN-BEI)

Phase II: Pt. 5 (1988, April 14/15 to April 30) Beijing, Xian, Shanghai

(It should be emphasized here that during my entire stay from 1988, April 14 to
29 the annual spring dust storms were blowing down from the Mongolian plains,
especially in Beijing and Xian. Therefore, I would consider the choice of

"spring-time" international conferences, symposia scheduling in Beijing or Xian not to be very attractive).

1988, April 15/16: Research Short Course Lectures on "Inverse Methods in Radar Polarimetry"

Beijing Institute of Technology

7, Bai-Shi-Qiao Lu

West Beijing

Prof. Li, Shi-Zi, Host (Editor, Antenna Sinica)

Mr. Wu, Chuan-Jie, Ph.D. Cand.

1988, April 18: Participation in Cultural/Social Events at BIT and invitation by President, BIT and Prof. Li, Shi-Zi.

1988, April 18-20: International Symposium on Radiowave Propagation, 1988, Fragrant Hills, Beijing

Prof. Lü, Bao-Wei, Academia Sinica, Electronics Div.

(W-M. Boerner, member, ISRP'86, Technical Committee)

Presentation of invited and four contributed papers

A.B. Kostinski and W-M. Boerner, (INVITED), "Formulation of Proper Standards in Radar Polarimetry," ISRP-88, Section 7, Paper No. 1, International Symposium on Radio Propagation, Fragrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.

B.D. James and W-M. Boerner, "Toward Increased Image Fidelity in Microwave Diffraction Tomography," ISRP-88, Section 7, Paper No. 2, International Symposium on Radio Propagation, Fragrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.

B-Y. Foo and W-M. Boerner, "On the Bistatic Formulation of the Physical Optics Inverse Scattering Problem in Radar Polarimetry and Imaging," ISRP-88, Section 7, Paper No. 5, International Symposium on Radio Propagation, Fragrant Hill hotel, Beijing, P.R. China, 1988, April 18-21.

A.B. Kostinski, B.D. James and W-M. Boerner, "On the Optimal Reception of Partially Polarized Waves," ISRP-88, Section 7, Paper No. 6, International Symposium on Radio Propagation, Fragrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.

A.P. Agrawal and W-M. Boerner, "On the Concept of Optimal Polarization in Problems of Radio Wave Propagation and Probing," ISRP-88, Section 7, Paper No. 8, International Symposium on Radio Propagation, Fragrant Hill Hotel, Beijing, P.R. China, 1988, April 18-21.

Introduction of/to many Chinese, Japanese and International experts in electromagnetic wave propagation scattering and remote sensing

Special Interests: Earthquake electromagnetic radiation precursor detection

Prof. Xiong Hao

Dr. Y.C. Zhang

China Res. Inst. of Radio Wave Propagation

P.O. Box 138

Xinxiang, Henan Prof.

(Tel Xinxiang 53912)

Prof. Li, Yan Tang

Dr. Guo, Yong
Earthquake Observatory
Handan Univ. of Science & Technology
Handan, Hebei Province

Dr. Zheng, Ying
Purple Mountain Observatory
Academia Sinica
Nanjing
(Lorran VLF Observatory: Recording of Shuttle Challenger
Explosion 1980 Jan. 28)

1988, April 21: Visit of PLA Air Force, Radar Research Institute: Dr. Wang,
Bei-De, Vice Director and Chief Scientist
Visit of Tsinghua Daxue, Information Electronics Dept. (Prof.
Yu, Ming)

1988, April 21-22: Visit of Peking Univ. and Presentation of Lectures
Hosts: Prof. Xue, Sheng-He
Prof. Jiang, Man-Ying
Mr. Wang, Bin, Ph.D. Cand.
Lectures on "High Resolution Polarimetric Radar Imaging."

1988, April 23-27: Xidian Daxue
Tai-Bai Lu 2
West Xian, Shaanxi Prof.
+(86)-29-55.801
Prof. Mao, Yu-kuan, Antenna Lab.
Prof. Ge, De-Biao, Physics Dept.
Prof. Liu, Yiang-Chua, Foreign Affair Office
Prof. Qiang, Bo-han, Electronics Dept.
Prof. Bao, Zheng, President

International Short Course Lecture Series on "Electromagnetic Scattering and
Inverse Scattering"

Main Lectures: Prof. Wolfgang-M. Boerner
(24 lecture hrs) UIC-EECS/CL
1988, April 25-27 Chicago, IL/USA

Prof. Pierre C. Sabatier
(24 lecture hrs) USTL-IMP
1988, April 27-29 Montpellier, Longuedoc, FR

04/27 Evening: Invitation by Prof. Bao, Zheng
President Xidian Daxue

1988, April 28: Visit of North West Polytechnic Univ. (Prof. Lin, Shi-Ming,
Prof. Huang, Zhang-Cheng): Expansion of NPU-UIC research
interaction

Visit of Ministry of Electronic Technology, Res. Institute No
20, Radar & Navigation (Dr. Zhang, Shi-Xiong)

Visit of Ministry of Defense and War, Radar Institute 206
(Dr. Wang, Yue)

Visit of Huang-He (yellow river) Factory, Radar Electronic
Div. (Mr. Zhang, Fan-Qi, Chief Engineer)

Visit of Academia Sinica, Optics Research Institute

1988, April 29: Visit of East China Normal Univ., NW Shanghai, Dept. of
Physical Electronics
Hosts: Prof. Chen, Han-Kui
Prof. An, Tong-Gi
Prof. Zhang, Xi-Mian

Presentation of Paper on "Recent Advances in Radar Polarimetry"

1988, April 30: Return Flight Shanghai-Narita-Seattle-Chicago (UA-890, UA-150)

CHAPTER II-2: SUMMARY OF ACADEMIC ACTIVITIES

II.2.1 Purpose of Interaction

During this Phase II interaction, research contacts established during Phase I were further strengthened and expanded in order to promote and advance acoustic/electromagnetic/seismo-electronic inverse methods in imaging sciences as applied to sonar/radar target analysis/detection/identification; radar meteorology; deep sounding sonar/radar; vector diffraction tomography in non-destructive material testing and medical diagnosis; and earthquake epicenter allocation based on electromagnetic earthquake precursor radiation analysis.

II.2.2 Invited Lectures (1 to 3) & Research Discussion (2-4 hours)

Japan: Tsukuba Daigaku (Applied Physics/Imaging Science Lab.); Tokyo Daigaku (Applied Physics/Theor. Electronics, EM Sounding/Radar Research Lab.); Denki Tsushin Daigaku, Sugudaira Space Wave Observatory & Earthquake Electromagnetic Precursor Radiation Detection Laboratory; Toyohashi Gijutsu Kagaku Daigaku (Electromagnetic/Biomedical Image Sciences Lab.); Nagoya Daigaku (Rock Fracture Electromagnetic Wave Emission Research Laboratory; Electro-tectonic & Seismo-Electromagnetic Wave Propagation Laboratory); Gifu Daigaku (Applied Math/Elmag. Imaging Lab.); Kamioka Neutrino Space Observatory (Neutrino Imaging Lab.); Toyama Doboku Kenkyo Jo (Polarimetric Meteorological Radar Observatory); Niigata Daigaku (Physical Electronics Department/Electromagnetic Imaging and Deep-sounding Lab.); Nagaoka Gijutsu Kagaku Daigaku (Electromagnetic Deep Sounding Lab.); Koganei-shi Radio Research Lab. (Radar Meteorology/Space Remote Sensing Lab.); Sagami-hara ISAS Res. Center (Electromagnetic Remote Sensing Lab.); Yokohama Furukawa Denko Research Center (Fiber-optics and Electro-optics R&D&E Manufactory Division).

P. R. China: Beijing Institute of Technology (Radar Electronics Department); Qing-Hua Daxue (Electrophysics Dept: Radar Imaging); Peking University (Physical Electronics Dept./Microwave Imaging Lab.); Xian Xidian Daxue (NWTEI: Radar Physics Dept./Radar Imaging Lab.); NW Polytechnical University Xian (Applied Math & Electromagnetic Wave Propagation Dept.); Xian Jiotong Daxue (Physical Electronics Dept.: Electromagnetic Deep Sounding/Imaging Lab.); Fudan Daxue/Shanghai (Electronics Dept./Electromagnetic Imaging Lab.); East China Normal Univ./Shanghai (Electronic Engineering Dept./Microwave Imaging/Measurements Laboratory).

II.2.3 Co-Chairman/Member of International Symposia, Workshops and Discussion Groups

- (1) 1988, March 28-31: Japan EIC Meeting, Waseda University, Takadano-baba Campus (Electromagnetic Inverse Methods in Electromagnetic Deep-Sounding)
- (2) 1988, April 18-21: P.R. China Symposium on Radar Propagation (Electromagnetic Inverse Methods & Remote Sensing), Fragrant Hill Hotel, Beijing (8 lectures).
- (3) 1988 April 25-29: Xidian Daxue (UNESCO/CAST) International Workshop on Electromagnetic Inverse Scattering & Remote Sensing (24 lectures).

II.2.4 Highlights of Interaction

Both in Japan and China, the novel fields of acoustic/electromagnetic/seismo-electronic inverse scattering and diffraction in radar remote sensing, geophysical deep sounding and medical diagnosis are expanding and advancing rapidly. Whereas in Japan, emphasis is placed on a pragmatic approach of simultaneous device/metrology development, in P. R. China theoretical, analytical and purely experimental analyses on a less technologically advanced level persist. Three major areas are currently being pursued most intensely: (i)

electromagnetic deep sounding with applications in sanitary engineering, mining and road construction; (ii) a very high number of different tomographic/MRI approaches in medical imaging and non-destructive material (plastic and ceramic) testing; (iii) the early detection of earthquake electromagnetic precursor radiation.

CHAPTER II-3: MAJOR OBSERVATIONS

Parallel with the strengthening of the Japanese Yen and its banking and industrial bases, we are witnessing a phenomenal expansion and advancement in academic, institutional and industrial research and development. It is a pure myth that Japanese research is still merely a vehicle on improving technological applications of known natural phenomena discovered elsewhere previously. Although during the fifties to early seventies the emphasis on pragmatic manufacture research was prevalent, we see excellent basic forefront research done in all disciplines in my field of expertise.

More so, I was very impressed by the sudden rapidly increasing number of foreign undergraduate, graduate, post-graduate students, postdoctoral fellows, scholars and visiting scientists/professors at almost every campus, invited during Phase II, i.e., we are witnessing a marked expansion of the Foreign Scholars program within a time-frame of only two years which can be backed up by statistics. It was also encouraging to notice that many European, North and South American, and Austral-Asian students have become rather cognizant in the use of the Japanese language which includes not only students enrolled in Far-Eastern languages and linguistics, but also in agriculture, science and engineering.

I was very impressed by the quality of the graduate academic teaching and research programs of my four host universities, Tsukuba Daigaku, Toyohashi Gijutsu Kagaku Daigaku, Denki Tsushin Daigaku and Niigata Daigaku and of the Tokyo Kogyo Daigaku Oakoyama and Suzukakedai campuses. The diligence, motivation, industry and happy scholarly atmosphere is to be highly praised. In fact, it is a real joy and academic pleasure to see my able hosts, Professors Kyohei Fujimoto and Kazuhiro Hirasawa, TUS; Yasumitsu Miyazaki and Mitsuo Yamaga, TIST; Takeo Yoshino and Tsutomi Suzuki, UEC; Takeo Abe and Masakazu Sengoku, NU; Toshio Sekiguchi; Naohisa Gotoh, Yoshiyuki Naito, Makoto Ando, and Matsuo Sekine, TKD move among and interact with their students and scholars, reminiscent of the early sixties in the USA. It would not be surprising to witness that within only a decade a great many foreign students will flock toward the Japanese Universities, where purity of knowledge and excellence in achievement are still considered the cornerstones of a sound academic research education. More so, because of the expansive instrumentation facility resources poured into Japanese Universities and research institutes surpassing any such trends we have experienced for a very long time in Northern America or Western Europe, it is clearly evident that the Japanese Science and Technology will further excell similar to the West German, Swiss and Scandinavian ones, during the next decades.

However, there still exists one rather sore, very observable ugly aspect about almost all Japanese University and College Campuses which must be entirely removed and improved, namely the rubbish, filth and dirt either on or in the vicinity of Japanese campuses. Whereas the rest of Japan by all standards ranks among the cleanest, tidiest and well groomed countries, its University campuses still are a disgrace inspite of the undeniable clean-ups accomplished. University campuses ought to be embedded in "mini botanic gardens" for the very essential and important educational goal of creating love, understanding and appreciation of the natural beauty of our terrestrial environment, and in order to instill the desire and dedication in all students of all branches of studies to strongly contribute to the retainment and improvement of our fragile natural environment including our flora, fauna, lakes and oceans, and our atmosphere.

CHAPTER II-4: SUGGESTIONS FOR IMPROVEMENT

Please, refer to my Phase I (1986 August 25) Final Report, Chapter IV: **Recommendations and Suggestions for Program Improvement**, Sects. 4.1 to 4.6. All of these suggestions still are valid and should be considered very seriously and therefore, are reproduced here in total. In the following, I am reemphasizing some of the very obvious shortcomings requiring immediate urgent improvements by bold-letter enhancement.

Although I found that almost all aspects of the visiting scientist/scholar programs administered by the Japan Society for the Promotion of Science are laid out in all minute detail and are being administered meticulously to the point, there are many suggestions which I wish to recommend for possible consideration.

Because of the diversified nature of "weak areas" of the program, I wish to categorize the problems under four major headings:

- II.4.1 Assistance for the Visiting Scholar from Abroad to Japan
- II.4.2 Provision of Carefully Selected Reference Material
- II.4.3 Improvement of University Campus Guest House Facility
- II.4.4 Improvement of University Campus Facility
- II.4.5 Improvement of Environmental Quality
- II.4.6 A Japanese Institute for the Promotion of Japanese Language and Culture

II.4.1 Assistance for the Visiting Scholar from Abroad to Japan

Whenever I was dealing with JSPS fellows in Japan or abroad, I found that those scientists and scholars were carefully selected, of very high international standards and in many cases highly renowned researchers, who deserve to be treated with the highest degree of respect and admiration. Most of us Senior Scientists have to adhere to very tight time schedules, satisfying very many different commitments which requires much more flexibility in settling and rearranging time schedules at the last minute, and also more efficient means of ferrying around in Japan.

In addition, the monthly stipends provided by JSPS in comparison to the living costs are not on a fair equitable level and certainly require respectable increases in order to make up for the inflationary cost increases and Yen versus dollar re-evaluations. Therefore, I would like to make the following suggestions:

II.4.1.1 Personal (Bilingual) JSPS Identification Pass

Every JSPS scholar from abroad visiting Japan be given bilingual cultural identification and similar to that provided, for example by the Alexander von Humboldt Foundation (see copy attached) clearly spelling out

- i) identification of the scholar (dates/place of birth, country of citizenship, personal biodata (height, color of eyes/hair, etc.), photo— in English and Japanese;
- ii) purpose of the mission of JSPS and that the holder of the "CULTURAL IDENTIFICATION CARD" is a guest of the Japanese government and should enjoy the assistance of all National Officers;
- iii) starting and completion dates of mission.

II.4.1.2 Flexibility of Dates of Tenure of Any JSPS Fellowship

Due to the multi/inter-disciplinary research involvement of many selected fellows, their broad set of local university and national responsibilities, increasingly more will require more flexibility of finalizing the program schedules, distribution of the program over many years, etc., and therefore the following is suggested:

- i) JSPS fellowships be distributed over a three-year duration with annually phased programs;
- ii) permission be given that during each month the scholar may

return home for the duration of one week in order to look after ongoing research programs if so required;

- iii) whenever possible JSPS fellows be given special highly price-reduced JRL monthly transportation passes in order to increase efficiency of movement.

II.4.1.3 Submission Date of Reports

In order to be of any assistance to JSPS regarding the submission of recommendations for program improvement, we Foreign Scholars require more time for absorbing all the new impressions which also may require intensive postprogram library studies; and therefore the following is suggested:

- i) instead of the stipulation of providing the final report one month after completion date of mission: 6 months after completion date;
- ii) completion date of program may mean six months after leaving the country in order to complete post-program library and reading studies;
- iii) in general, I found the meticulous handling of overly fixed deadline dates very annoying and counterproductive;
- iv) for Senior Scientists, allowances for sudden program changes must be accommodated if those result from national duties of the home base.

II.4.1.4 Bank Credit Card

I found it next to an absolute insult that I was not allowed to possess a Japanese Bank Credit Card because I was not staying for a period longer than six months. Therefore, I would like to suggest, because without a Credit Card no one can exist nowadays, the following:

- i) every JSPS fellow from abroad coming to Japan even for a period of only one (1) month be made eligible to receive a Bank Credit Card of any of the major Japanese banks;
- ii) the limited banking cards for handling of checking accounts be made bilingual (certainly a JSPS-identification card could be very useful!).

II.4.1.5 Increase of Daily Allowances, Honoraria and Travel/Research Contributions by JSPS

Certainly, the largest number of possible fellowships should be created, but compensation must keep abreast with inflationary cost increases as well as with the Yen devaluation/evaluation. This is a very important issue and should be considered of great urgency. I will summarize my case in stating that if I had to rely only on JSPS resources then I would (as I really did) live on a "graduate student budget" or even less! Under no circumstances would I be able to sustain the support of my wife and definitely not my children to accompany me as much as those would have loved to do!

II.4.2 Provision of Selected Reading Material for JSPS Scholars Selected from Abroad to Visit Japan

Although we can obtain a lot of useful material about travel in Japan from JTB, for most of us true scholars very little is provided on serious reading material on an amateur expert level and only by trail-and-hit method may one be successful in identifying the truly good and reliable up-to-date resource material in the English, German, French and/or Russian languages. To my greatest astonishment many of the renowned works were available in only the big bookstores, e.g., Maruzen in Tokyo, Osaka or Kyoto and one had to order those with six week waiting periods.

Since I want to come very well prepared in the future, I request that to me and all other JSPS-fellows a detailed list of pertinent reference material be provided with source of distribution and a yearly, updated schedule.

II.4.2.1 Bilingual Cartographic Maps and Atlases

It is very hard to find good updated bilingual maps and atlases which one ought to have studied carefully in advance:

- i) bilingual road maps;
- ii) bilingual historical maps;
- iii) bilingual geographic maps;
- iv) bilingual atlas (e.g., TEIKOKU's Complete Atlas of Japan).

II.4.2.2 Basic Textbooks on Japanese Language

Although I was provided with great many simplistic texts on how to acquire a knowledge of the Japanese language, I found that a survey conducted by a team of Japanese experts and overseas scholars would be very useful on this subject matter.

II.4.2.3 Basic Texts on the Historical Development of Japanese Literature, Music, Philosophy and Religion

Although a great many books are available, I soon found out that the quality and depth varies widely and indeed JSPS could provide an excellent service in identifying the best source books for specific applications. See, for example, the excellent historical treatise on China

C. Blunden and M. Elvin, Cultural Atlas of China, Facts on File, Inc., 460 Park Ave. South, New York, N.Y., 10016 (+1-800-322-8755).

II.4.2.4 Bilingual Nature Field Books on Japanese Flora, Fauna, Geology, Oceanography, etc.

It would assist us a lot to find bilingual field books on Japanese flora, fauna, geology, oceanography, etc., which I found to exist in selected fields or sub-fields, however mostly unknown even to the experts. Again, JSPS could provide an excellent service by providing a list of such books.

II.4.3 Improvement of University Guest House Facilities

I found all of the University guest house facilities to be very clean, well groomed and looked after. However, I certainly missed certain important facilities such as

- (i) Electric Washing and Drying Machines: It is very inconvenient to run all over the neighborhood, for example during heavy monsoon rains or take the subway two to three stations to find an operational laundry washing and drying slot machine facility. Note, I did not find a single laundry washing/cleaning business that would accept underwear, socks, woolen pullovers, etc.
- (ii) International Telephone Calling facilities should be installed in all of the University guest houses and/or libraries. I find the telephone paycard (for a fixed number of calls, say 5000 yen) a great invention and such could be used most favorably. Note, that for visitors from North America or Europe, we must usually make calls during the night!
- (iii) Although most guest houses do possess stand-off elevated toilet facilities, some don't; and many office and laboratory buildings don't! For us foreigners of Northern Occidental/American upraising, we are unaccustomed to the use of ground-based sub-surface facilities!

II.4.4 University Campus Clean-up

With the exception of Waseda University, I found almost all campuses of Japanese Universities to be very untidy, dirty, and uncared for. For a foreign visiting scholar, who was taught at home that the Japanese are some of the cleanest and neatest people, it really hurts to see such an awful dirty mess on the campuses and in the immediate neighborhood of any campus (including Waseda).

If we cannot instill in our most talented group of growing citizens the drive for cleanliness and quality of the environment, how should we expect the rest of the population to behave!

- (i) Introduce Campus Clean-up Days (one per week);
- (ii) Provide more waste baskets (including receivers for cigarette buds);

- (iii) Keep lavatories and toilets cleaner and provide more western style facilities;
- (iv) make sure that canteen food services are clean (note, I found spoons and cups at times to be very dirty!);
- (v) More attention should be paid to environmental beauty on all campuses. Japan is now wealthy enough to afford the expenditures for campus clean-up and beautification.

II.4.5 Improvement of Environmental Quality: Water, Land, Air and Health

Being of German descent and having had to suffer a lot during all of my life in "foreign countries for being a German in origin" and in Germany for being an "Auslandsdeutscher", I feel confident to state that I very well understand how the Japanese people must feel when they are continuously attacked by hostile foreigners because of their self-centeredness, their cultural, social and religious homogeneity and especially because of their dedication, discipline and industry. I admire the Japanese people, and they, more than any other people, have currently the most to offer to all nations in enriching man's life and understanding of the universe.

However, the Japanese people have sacrificed a very great lot during the past century, namely environmental quality and may be more (or less) than any other country. This obviously apparent severe problem, yet, has been recognized and the Japanese people indeed are worried about Environmental Quality, but many of their industrial leaders believe enough has been done. I am personally convinced that this is not the case! On the other hand I am convinced that only a highly technologically developed country with highly disciplined and industrious people, such as Japan has to offer, will be able to achieve the long-desired breakthrough everyone is waiting for.

Therefore, I would like to propose to all of my Japanese hosts, colleagues and peers in all walks of life to make "The Quest for Environmental Quality" their first utmost goal which includes over many years to come:

II.4.5.1 Beautification of Architecture

- (i) beautification of streets, roads and highways;
- (ii) beautification of architecture and removal of ugly post-WWII tin sheds sprawling all over the place;
- (iii) beautification of architectural styles for landscaping, housing etc., in finding a harmonious balance with traditional Japanese styles;
- (iv) beautification of University, Institute and Industry Company building complexes in harmony with traditional Japanese styles.

II.4.5.2 Quality Control of Air

Although a lot has been achieved over the past decade, still Japan must do much more to improve on the Quality of Air and reduce pollution:

- (i) develop and advance the technology for electro-combustion engine-powered vehicles as a decisive means of cutting down on urban area vehicle exhaust pollution;
- (ii) develop and advance technology for extraction of smoke and poisonous gases from smoke stack exhaust, etc.;
- (iii) introduce core courses at all educational levels (elementary, secondary, high school, college, university) on air quality control.

II.4.5.3 Quality Control of Water

Although I found many Japanese rivers and waters cleaner than ever before, not only in Japan but the world over must we be very concerned about the maintenance and improvement of the quality of both fresh and sea water:

- (i) improve sewer systems in rural areas;
- (ii) strictly deny permission for the use of gasoline powered motors or any oil releasing vehicles on inland lakes, reservoirs and precious coastal waters;
- (iii) do not permit uncontrolled urban sprawl into valuable farming

- and natural lands;
- (iv) keep forests and rural areas free of waste materials, especially chemicals, used Cadmium-Nickel batteries, tires, etc.;
- (v) introduce core courses at all educational level (elementary, secondary, high school, college, university) on water quality control.

II.4.5.4 Quality Control of the Acoustic and Electromagnetic Propagation Medium

It is a pleasure to understand that Japan has accomplished the most of any industrialized nation in reducing acoustic and electromagnetic radiation noise sources. Yet all of us have not paid sufficient attention to this very serious environmental radiation noise problem.

Although we have all been shocked about the serious after-effects of the Chernobyl disaster, not to forget Hiroshima and Nagasaki, we yet also need to make the general population aware of the damage to nature and the health of living creature any type of acoustic as well as electromagnetic overdoses of radiation may cause:

- (i) introduce very strict regulations on radiation level of loud speakers and any other public or inhouse use of acoustic noise/radiation sources which includes modern entertainment music;
- (ii) introduce much stricter industrial codes and standards on radiation level of acoustic and electromagnetic radiation equipment of all types used anywhere close to nature and living creatures;
- (iii) develop and advance the technology for planning all transmission line (energy plus communications) systems underground in well shielded ducts;
- (iv) eliminate line of sight microwave radiation links by fibre optical information transmission systems;
- (v) introduce core courses at all levels (elementary, secondary, high school, college, university) on acoustic and electromagnetic radiation quality control.

II.4.5.5 Quality Control of Health of Living Creatures as a Whole

It is not sufficient that we only be concerned with the quality control of the health of people, but we must be concerned with that of the health of all living creatures otherwise we may be choosing only short-term solutions and create much more serious problems for the prolonged existence of the human race and its co-inhabitants of the terrestrial sphere and the universe:

- (i) introduce more awareness of the value and respect for living creatures as all of our religions, East and West alike, are demanding from us!
- (ii) although I have found some concern about these issues, absolutely no sufficient steps are taken at an overall concerted effort world-wide!
- (iii) introduce courses at all educational levels (elementary, secondary, high school, college, university) on more devotion and religious respect for any creature.

Note, I wish to re-emphasize that I am addressing this specific problem because I am convinced that it only can be the Japanese people who, armored with their science and technology, paired with their deep religious devotion to nature, will be able to provide the leading advances in addressing this problem very realistically.

II.4.6 Creation of an International System of National Institutes of Japanese Culture and Language

During the post-WWII period and thereafter, Japan has attained a very high standard of technological, scientific but also social, linguistic and cultural accomplishments. All of us visitors to your beautiful country and meeting your

talented hardworking people know that the Japanese way of life has many positive sides which have a lot to offer to the entire world and every other nation. For example, here I recall the Goethe Institutes of German Language and Culture, and I am sure that Japan has to offer a lot on a similar scale. Maybe the theme need not be based on one of your famed poets, writers and thinkers, but more on one of your great masters of the fine arts, for example of Ukiyo-E, such as Hiroshige or Hokusai, known already far beyond the shores of Japan.

Certainly, there exist so many reasons why Japan should create such a chain of international cultural institutes and there exist many more reasons why we foreigners should encourage the Japanese people to do so, namely to share with all others the fruits of the hard labor for the hard-fought advances in the sciences, the arts and technologies which ultimately lead to the enrichment of culture.

Thus, may I suggest for consideration:

- (i) the Japanese people create for the benefit of their own and foreign people an international chain of national Japanese institutes of culture;
- (ii) provide lectures, seminars, short courses, performance examinations on Japanese language, literature, art, fauna, flora, geology, sociology, etc.;
- (iii) invite future JSPS fellow awardees to participate in a six week to three month cultural accommodation program (similar to one by the Goethe Institute, for example);
- (iv) provide a national workshop gathering once or twice a year for all JSPS fellows, who are carrying out their tenure during that period in Japan;
- (v) create a JSPS newsletter for program continuation and updates to be distributed to all former JSPS fellow awardees;
- (vi) hold weekly open houses at JSPS headquarters or the desired cultural centers for increased interaction of current JSPS fellows with Japanese scholars and scientists;
- (vii) finally, once a year, we JSPS fellow awardees from abroad should be invited to meet with the dignitaries of the Japanese government and society.

CHAPTER II-5: SUMMARY OF P.R. CHINA TRAVEL

Similar to my previous recent visits to the People's Republic of China, I was amazed about the progress made in restructuring and rebuilding its cities, roads and production systems both in urban and rural regions.

However, we also witnessed a rather steep inflationary trend which might have serious repercussions because it is evident that only a small section of the total population is profiting from the new approach, i.e., merchants, farmers and those who have the facilities to produce and sell goods. On the other hand, the working class, including teachers, professors, scientists, etc., are suffering from the steep price increases at constant salary levels. Therefore, it is not surprising to encounter many more unfriendly grim faces in comparison to only two years ago. In case these trends of too rapid advancements prevail for too long, a backlash similar to those which caused changes in Iran may occur in the not so distant future!

Although the overall construction pace is mind boggling, it is yet disappointing to see how little resources are flowing toward academic institutions for facilities upgrading and expansion relative to the general high rise building and hotel construction boom. We were also given notice that the number of students, scholars and professors selected for studies in other countries, mainly Japan, Northern America, Western and Eastern Europe and Russia will be drastically reduced and that the total number of scholarly visitors (all inclusive) from P.R. China to the USA, cannot exceed 20% (as compared to the current 55%), whereas that to Japan is to increase to 20% from about 5%.

Therefore, our Japanese colleagues will be requested to strengthen their academic interaction with the Chinese counterparts. Certainly, this is a great opportunity which must be analyzed with great care because we are already witnessing some counter-productive competitive moves of weighting US versus Japanese versus European graduate education programs, etc.

In my opinion, which I am confident is being shared by many, it would serve the active international academic research community best if a system of multinational inter-US-Japan-Europe-Austral-Asia-China scholarly exchange system could be devised. For example, one could create international blocks or consortiums of universities by selecting one or several universities of each country with active participation of the academic staff, i.e., exchange students could not only visit one but several foreign countries.

It should also be noted that US, Japanese, European and Austral-Asian students and scientists would gain in academic research experience and education by studying in or carrying out research in China. Unfortunately, all too little is done on all sides. Because of the rather restricted number of Chinese students selected to study abroad, it is not surprising to learn that not so fortunate students try to find a study opportunity abroad by their own, thus flooding the Western countries, especially the USA, with applications. Procedures for handling these severe problems in a fair and responsible manner on both sides are in desperate need. Outsiders who have not been made to comprehend the disastrous damages done to the Chinese academic and scientific sphere of life during the years of the Cultural Revolution must be better informed and invited to participate in rebuilding the scholastic and educational system which was almost also totally erased during the infamous "Cultural Revolution" next to destroying so many historical sites and national Chinese treasures.

Because of the complete imbalance between number of people and available national plus international resources, the People's Republic of China will have to strengthen its purge of reducing the number of its citizens drastically, i.e., from the current 1.1 billion to considerably less than 600 million within the next fifteen to twenty-five years. Otherwise, the People's Republic of China will fall further behind in almost every department because all available resources are required to feed the masses and keep them "healthy" but unfortunately illiterate due to the evident lack of teachers and resources, etc.

In summary, all of us, the People's Republic of China and we around this great country must combine our efforts to bring about a mature solution to re-establishing a solid, broad educational system in China, otherwise, we all-together are heading again toward very dark ages.

CHAPTER II-6: ACKNOWLEDGEMENTS

First of all, I would like to thank Professor Kyohei Fujimoto and Mrs. Yuko Furukawa of the JSPS Administration Office in the Yamato Bldg. of Chiyoda-ku for their valuable assistance and harmonious collaboration in securing the second JSPS Senior US Scientist Fellow Award and for making the Phase II interaction another unforgettable event.

The interaction among my many hosts, foremost Professor Kyohei Fujimoto, Kazuhiro Hirasawa, Yasumitsu Miyazaki, Takeo Yoshino, Toshio Sekiguchi, and Takeo Abe in Japan, and Professors Lü Bao-Wei, Li Shi-Zhi, Jiang Man-Ying, Xue Cheng-He, Mao Yu-Kuan, Ge De-Biao, Lin Shi-Ming and Chen Han-Kui of the People's Republic of China and myself was excellent and I want to express my sincerest thanks to them for their hospitality and generosity, and for opening so many doors wide for me to become a lasting friend of the Japanese and Chinese people.

At all of the host universities in Japan and in China, I was offered to stay at their unique guest facilities on campus or in nearby dedicated hotels which I enjoyed and I was very grateful for. Thus, I wish to take this opportunity and express my sincere gratitude also to the senior administrators, Vice Presidents and Presidents who offered me the use of these facilities.

Similarly, I would like to thank all of the administrators of the other organizations who with their devoted and enthusiastic collaboration made these cultural and research travels possible, including, Dr. George B. Wright, ONR/Far-East; our director of international affairs, Dr. Susan Lourenco; my department head, Prof. Wai-Kai Chen; and my deans, Dr. Paul M. Chung and Dr. Phillip L. Hawley of the University of Illinois at Chicago. In addition, I would like to thank my research contract scientists and monitors Drs. Kenneth Davis, Arthur K. Jordan, James G. Smith, ONR; Drs. Robert J. Dinger, Guenter Winkler, Brett Borden, NWC; Drs. Otto Kessler, Raymond Dalton, NADC; Dr. Karl H. Steinbach and Mr. Donald Franklin, BRDEC; Drs. James W. Mink, Walter Flood, ARO; and Drs. Fred Sedenquist, Robert J. Russell, Lloyd W. Root, MI-LAB, for their interest in our research collaboration.

Finally, I wish to thank my family and in particular my dear and brave wife, Eileen-Annette, for enduring the many hours I have spent away from home, and for being so accommodating during the struggles of having the FINAL REPORT prepared, edited and typed next to fulfilling so many other commitments at work and home.

On Foundations of Radar Polarimetry

A. B. Kostinski
W-M. Boerner

ERRATA for "On Foundations of Radar Polarimetry," T-AP/34/12/10041

1. Equation following Eq. 2, p. 1396, (top of second column). The subscripts (\hat{e}_1, \hat{e}_2 -plane) and (\hat{x}, \hat{y} -plane) are interchanged, and it should read:

$$\underline{E}_T = \begin{bmatrix} \cos \gamma_T \\ \sin \gamma_T e^{j\phi_T} \end{bmatrix}_{(\hat{e}_1, \hat{e}_2\text{-plane})}, \quad \underline{E}_R = e^{j\alpha_R} \begin{bmatrix} \cos \gamma_R \\ \sin \gamma_R e^{j\phi_R} \end{bmatrix}_{(\hat{x}, \hat{y}\text{-plane})}$$

2. End of first paragraph (top of second column, p. 1396). The sentence, "The linearity of Maxwell's equations....," is incorrect and should be disregarded.

3. Section IV, third paragraph, p. 1397. Instead of " $||h|| = ||ET|| = ||ER|| = 1$ " it should read " $||h|| = ||ET|| = 1, ||ER|| \neq 1$, but it is the optimization variable."

4. P. 1400, middle of left column (before "which gives....").

$$\frac{1}{2} \begin{bmatrix} 1 & -j \\ 1 & +j \end{bmatrix} \text{ should read } \frac{1}{2} \begin{bmatrix} 1 & -j \\ 1 & +j \end{bmatrix}.$$

5. P. 1400, right column, following Eq. 17. Brackets are missing, and it should read $a = (\lambda_1 - g_{11})/g_{12}$ instead of $a = \lambda_1 - g_{11}/g_{12}$.

6. P. 1403, last line before ACKNOWLEDGMENT. The equation (superscript T),

$$[U] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}^T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \text{ should read } [U] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix}^T.$$

On Foundations of Radar Polarimetry

ALEXANDER B. KOSTINSKI AND WOLFGANG-MARTIN BOERNER, FELLOW, IEEE

"... Circularly polarized waves have either a right-handed polarization or a left-handed polarization, which is defined by convention. The TELSTAR satellite sent out circularly polarized microwaves. When it first passed over the Atlantic, the British station at Goonhilly and the French station at Pleumeur Bodou both tried to receive its signals. The French succeeded, because their definition of sense of polarization agreed with the American definition. The British station was set up to receive the wrong polarization because their definition of sense of polarization was contrary to our definition ..."

from J. R. Pierce, *Almost Everything About Waves*. Cambridge, MA: MIT Press, 1974, pp. 130-131.

Abstract—Polarization aspects of the radar target scattering problem are reexamined. The optimization problem of radar polarimetry is formulated and Kennaugh's method of finding optimal polarizations is modified and extended to nonreciprocal and bistatic cases. Our approach does not necessitate diagonalization of the target scattering operator and therefore, a change-of-basis is not required. The change-of-polarization-basis is motivated by the comparison of experimental data taken with different antenna sets. Unitary matrix algebra is used to derive proper transformation formulas for scattering operators and bilinear voltage forms.

I. INTRODUCTION

IT HAS BEEN ABOUT 37 years since the target polarization scattering matrix [1] and the optimal polarization concept [2] have been introduced. In view of the rapidly increasing amount of literature on the subject, a careful reexamination of the foundations of radar polarimetry is in order.

Indeed, there are several monographs [3]–[6] devoted solely to the depolarization of the electromagnetic waves, one of which deals exclusively with radar polarimetry [6]. The monograph by Bogorodsky *et al.* [4] and the ellipsometry text by Azzam and Bashara [5] are, in our opinion, very useful mathematical treatments, while Beckmann's book [3] offers more physical insight into various depolarization processes. Our goal here is to reestablish the conceptual foundations of radar polarimetry as clearly as possible and show its immediate implementation. The main objective is to help the radar operator to take advantage of these polarization properties by utilizing the information contained in the target scattering

matrix, the measurement of which has become possible due to the technological advances of recent years [7].

II. CHOICE OF THE COORDINATE SYSTEM CONVENTION

Two-Dimensional Polarization States

In this paper, we will consider polarization dependence of various radar target scattering processes as seen at the receiving antenna terminals, i.e., at a fixed point in space. We therefore agree entirely with a classic reference [8] on the subject that "... In discussing radar scattering it is convenient to use the same coordinate system for both the transmitted and back-scattered fields ..."

Let us define the origin of the coordinate system at the receiving antenna terminals and let the z -axis be directed from the receiving antenna toward the target as shown in Fig. 1. The x and y axes are chosen to form a right-handed triplet with the z -axis, and unit vectors \hat{e}_1 and \hat{e}_2 are in the polarization plane of the transmitted wave, i.e., perpendicular to its direction of propagation \hat{r} as shown in Fig. 1. Only in the case of backscattering do \hat{e}_1 and \hat{e}_2 coincide with \hat{x} and \hat{y} (Fig. 2). In the far field and for small (compared with distance r) targets, the waves can be treated as plane. Thus

$$\vec{E}_T = (E_T^2 + E_T^2)^{1/2} [\cos \gamma_T \hat{e}_1 + \sin \gamma_T e^{j\phi_T} \hat{e}_2] \cdot \exp j(\omega t - kr + \alpha_T) \quad (1a)$$

$$\vec{E}_R = (E_R^2 + E_R^2)^{1/2} [\cos \gamma_R \hat{x} + \sin \gamma_R e^{j\phi_R} \hat{y}] \cdot \exp j(\omega t + kz + \alpha_R) \quad (1b)$$

$$\vec{H} = (h_x^2 + h_y^2)^{1/2} [\cos \gamma_h \hat{x} + \sin \gamma_h e^{j\phi_h} \hat{y}] \cdot \exp j(\omega t - kz + \alpha_h) \quad (1c)$$

where in all equations, $\gamma \equiv \tan^{-1}(E_y/E_x)$, ϕ and α are the relative and absolute phases, respectively, subscripts T and R stand for transmitter and receiver, and \vec{H} is the wave which the receiving antenna would radiate in the $+\hat{z}$ direction if it acted as a transmitter. Note that in the case of backscattering $\vec{E}_T = \vec{H}$ only if the same antenna is used for transmitting and receiving. From here on, we will operate with the expressions in square brackets in (1a)–(1c) written as complex two-dimensional column vectors (for instance, see definition of the Jones vector in [5] and references therein), which define the polarization state (PS) of the wave and are denoted with a bold letter, e.g.,

$$\mathbf{E}_T = \begin{bmatrix} \cos \gamma_T \\ \sin \gamma_T e^{j\phi_T} \end{bmatrix}$$

Note that PS determines completely the polarization ellipse of

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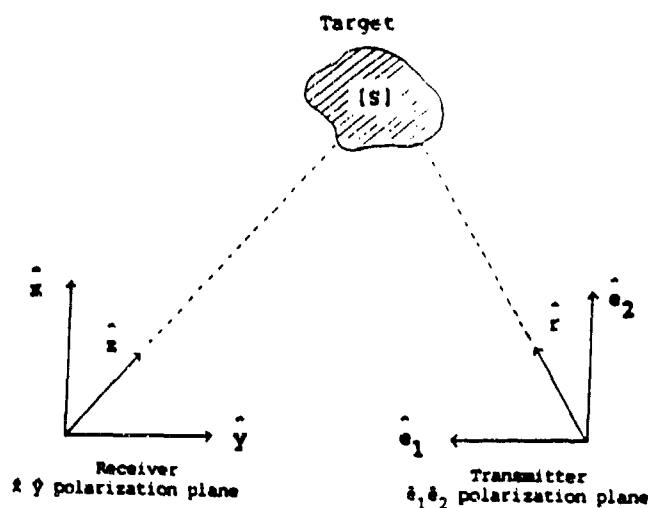


Fig. 1. The general bistatic arrangement.

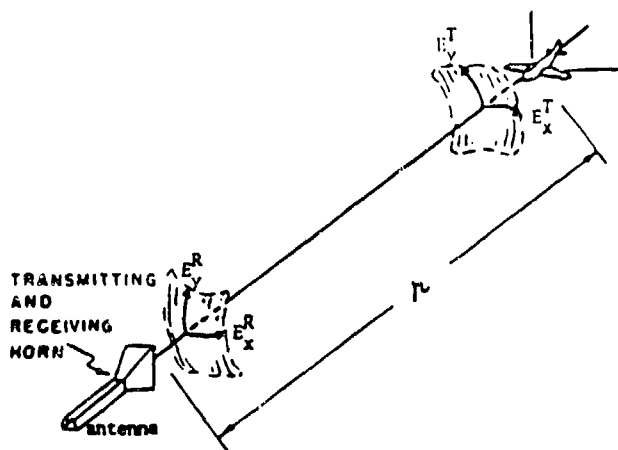


Fig. 2. Radar course illustrating incident and reflected wave fronts (borrowed from [2]).

the wave at a fixed point in space [9] (in this paper—at the receiving antenna terminals) and direction of “viewing” is always along $+\hat{z}$ for all waves involved. The direction of propagation for any given wave can always be recovered from the exponents in (1a)–(1c), but is not contained in the polarization state of the wave. Thus, according to (1a)–(1c), E_T , E_R , and h propagate in the $+\hat{r}$, $-\hat{z}$, and $+\hat{z}$ directions, respectively. Therefore, a PS given by, say $1/\sqrt{2}[1]$, may characterize a circularly polarized h (it is left hand circular (LHC), because of $+\hat{z}$ propagation) or a circularly polarized E_R (it is right hand circular (RHC) with $-\hat{z}$ direction of propagation).

III. BASIC EQUATIONS OF RADAR POLARIMETRY

There are essentially two equations that form the basis of radar polarimetry. They represent the polarization-dependent features of the electromagnetic scattering process and the radar reception of the returned signal. One might say that both field theory and network theory contribute to radar polarimetry. Let us start with the electromagnetic scattering process illustrated in Fig. 1 and define the scattering matrix by the following equation:

$$E_R = \lim_{r \rightarrow \infty} \left\{ \frac{\lambda}{(4\pi)^{1/2} r} \right\} [S] E_T, \quad (2)$$

where, as before

$$E_T = \begin{bmatrix} \cos \gamma_T \\ \sin \gamma_T e^{j\phi_T} \end{bmatrix}_{x,y\text{-plane}} \quad E_R = e^{j\alpha_R} \begin{bmatrix} \cos \gamma_R \\ \sin \gamma_R e^{j\phi_R} \end{bmatrix}_{x_1,x_2\text{-plane}}$$

Here, the origin of time is chosen to set the absolute phase α_T of E_T to zero. The distance between the receiving antenna and the target and the operating wavelength are denoted by r and λ , respectively, and α_R is the absolute receiver phase. Note that the far-field assumption [1], [2] is employed, that $[S]$ is dimensionless, and that the proportionality factor in (2) is omitted from here on. The linearity of the Maxwell equations allows one to write down (2), but elements of $[S]$ are, in general, complicated and sensitive functions of frequency, target orientation/aspect, relative position of the polarization planes in the bistatic case, etc.

Another fundamental equation of radar polarimetry comes from a different aspect of the problem—the receiving antenna network. It is the voltage equation which relates the voltage measured at the receiving antenna terminals to the polarization of the incoming (scattered) electromagnetic field, which in turn, can be related to the incident field through the scattering matrix via (2). An excellent recent derivation of the voltage equation in terms of crossed dipoles is given in [10], but it was first introduced in [1], [11], [12] as

$$V = h^T E_R = h^T [S] E_T \quad (3)$$

where the notation $a^T b = a_x b_x + a_y b_y$ is for column vectors, superscript T denotes the transpose and all quantities are normalized to unity in order to concentrate on polarization properties. The “antenna height” h [10]–[12] is defined here as a polarization state of the transmitted wave which would result if the receiving antenna were to transmit in the direction of the target. Thus, h is a directly measureable quantity. It is defined on the basis of the radiation pattern of the receiving antenna. Several remarks must be made about (3). First of all, one notes that (3) is not of an inner product form because h is not conjugated. In particular, the maximum condition for V is $h = E_R^*$, rather than $h = E_R$ provided $\|h\| = \|E_R\| = 1$. One must remember that conjugation of any PS reverses the sense of rotation of the corresponding polarization ellipse, and therefore, the maximum voltage condition $h^* = E_R$ has a definite physical meaning: this “polarization match” condition states that the returned wave is matched to the receiving antenna when its polarization ellipse is oriented in space identically with the one due to h (radiated by the receiving antenna when used as a transmitter), but has opposite sense of rotation when both are viewed from the origin in the $+\hat{z}$ direction.¹ Also note that both h and E_R (or $[S] E_T$) are defined in the \hat{x}, \hat{y} -plane so that even in the bistatic case, the vector product in (3) is well defined. Finally, we would like to

¹ Such a polarization match requirement is rather obvious in case of linear polarizations since it demands that the two vectors be aligned. It is less obvious in a case of circular polarizations, and perhaps, the following helps to visualize the result. If one designs two identical helical antennas and then lets them face each other, they turn out to be polarization matched. To appreciate the significance of this fact, please turn to the epigraph under the title.

point out that (3) is a result of network theory, and therefore it is in a certain sense less general than (2) because it is conceivable that the receiving circuits may be designed to obey equations different from (3).

Practical applications of the above equations are numerous [3]–[6] and can be broadly classified into three categories: optimization/signal enhancement, discrimination against unwanted signals (clutter suppression), and classification of targets. The first two are direct, and the third is an inverse problem.

The optimization, for instance, may involve maximization of the voltage form given by (3) for a given target (known scattering matrix) by properly choosing the polarization of the transmitted field \mathbf{E}_T . Similarly, one would want to minimize the voltage due to clutter, etc.

IV. VOLTAGE OPTIMIZATION AND OTHER APPLICATIONS

Our approach here will be phenomenological in that we assume a complete knowledge of the target scattering matrix from the outset (measured or calculated, monostatic or bistatic) and seek ways to use the information contained in $[S]$.

Let us start by precisely formulating the voltage optimization problem: find such polarizations of the transmitting and the receiving antennas that for a target of known scattering matrix the voltage developed across the receiving antenna terminals is maximized.

Mathematically it translates into: find \mathbf{E}_T and \mathbf{h} such that $V = \{\mathbf{h}^T [S] \mathbf{E}_T\}$ is maximized for a given $[S]$ and subject to the conditions $\|\mathbf{h}\| = \|\mathbf{E}_T\| = \|\mathbf{E}_R\| = 1$. This problem, known as a search for optimal polarizations, was previously formulated and partially solved for the monostatic case in [2]. Further work can be found in [6], [8], [13]–[17].

Here, we offer a novel approach to a problem which, in our opinion, has two significant advantages over the previous work [2], [4], [6], [8], [13]–[17]. Firstly, such a three-step approach is more transparent in terms of the physical interpretations and secondly, it does not involve diagonalization of $[S]$, and thereby the use of unitary change-of-basis matrices is not necessary. Such a formulation allows one to use a well-known theory of Hermitian forms [18], [19] unlike the work in [2], [6], [13]–[15] which relies on a certain "pseudo-eigenvalue problem," the physical meaning of which is not entirely clear. Furthermore, it enables one to treat symmetric, asymmetric, monostatic and bistatic cases in an identical manner and the procedure can easily be generalized to several Hermitian forms (targets) which are very useful in signal-to-noise/clutter ratio-type of problems [17], [18].

The problem is solved in three stages. First, the expression for power in the scattered wave is found in terms of the scattering matrix elements and the transmitted wave. Then, the corresponding Hermitian form is maximized to find an optimal transmitter polarization and the scattered wave due to such polarization is computed. Finally, the receiver polarization is adjusted to match the polarization state of the scattered wave.

Stage 1

The total normalized power (energy density) P_w in the scattered wave is given by $\mathbf{E}_R^* \mathbf{E}_R$; where $*$ \equiv $(*)^T$ stands for

a Hermitian conjugate. Substituting for \mathbf{E}_R in terms of \mathbf{E}_T from (2a) one obtains

$$P_w = \mathbf{E}_R^* \mathbf{E}_R = ([S] \mathbf{E}_T)^* [S] \mathbf{E}_T = \mathbf{E}_T^* [S]^* [S] \mathbf{E}_T \\ = \mathbf{E}_T^* [G] \mathbf{E}_T. \quad (4)$$

Since the Graves power matrix $[G] \equiv [S]^* [S]$ is for any $[S]$ a Hermitian matrix [7], P_w is given by the Hermitian form (4), and our goal is to find such an \mathbf{E}_T that P_w is maximized for a given $[S]$, subject to the "unit circle constraint." Linear-algebraic details of the above problem are given in Appendix I, and we need only to point out here that the solution is essentially given by a well-known theorem about extremal properties of Hermitian forms [18]–[20], which states that the extremum is achieved by a vector satisfying the following eigenvalue equation:

$$([G] - \lambda [I]) \mathbf{E}_{T, \text{opt}} = 0, \quad (5)$$

where $[I]$ is the identity matrix and the maximum is achieved by \mathbf{E}_T corresponding to the largest (minimum—for the smallest one) eigenvalue.² The eigenvalues are real and the eigenvectors are orthogonal. The explicit solution for the eigenvalues is given in the (2×2) —complex case by a simple quadratic equation

$$\lambda^2 - (g_{11} + g_{22})\lambda + (g_{11}g_{22} - g_{12}g_{21}) = 0 \quad (6)$$

where the g_{ij} are the elements of the Graves power matrix $[S]^* [S] \equiv [G]$. Substituting the eigenvalues (λ_1, λ_2) from (6) into (5) and solving for the components of $\mathbf{E}_{T, \text{opt}}$ essentially completes the first stage. Physically, the eigenvalues correspond to the maximum and minimum of the energy density of the reflected wave in the given direction as a function of the transmitter polarization. Note that λ_1 and λ_2 are real because $[G]$ is Hermitian which agrees with their physical interpretation as power. When a target is very "transparent," the eigenvalues are small compared with unity.³ We should note that $[G]$ has only four free parameters, unlike $[S]$ which has five (seven) in the symmetric (asymmetric) case [14]. Further details and explicit expressions for the eigenvectors in terms of $\det [G]$ and $\text{Tr}[G]$ are given in Appendix I, while numerical examples and the relation to Kennaugh's symmetric case procedure are examined in Appendix II.

Stage 2

Equation (5) gives $\mathbf{E}_{T, \text{opt}}$, i.e., the polarization state of a transmitter such that the power in the scattered wave is maximized. We now compute this scattered wave by using the known scattering matrix $[S]$. Hence,

$$\mathbf{E}_{R, \text{opt}} = [S] \mathbf{E}_{T, \text{opt}} \quad (7)$$

so that the scattered polarization state is completely specified.

² The fact that optimization of the Hermitian form (4) leads to the eigenvalue equation (5) is basically a linear-algebraic generalization of the fact that a quadratic function extremum is given by a linear equation after taking a derivative.

³ Such "transparency," of course, is not necessarily related to the material, but mostly to the specular point geometry.

Note, however, that in general $\mathbf{E}_{R, \text{opt}} \neq \mathbf{E}_{T, \text{opt}}$ because eigenvectors of $[\mathbf{S}^*][\mathbf{S}]$ are not necessarily eigenvectors of $[\mathbf{S}]$, unless $[\mathbf{S}]$ is normal, i.e., $[\mathbf{S}]^*[\mathbf{S}] = [\mathbf{S}][\mathbf{S}]^*$. Further mathematical details are given in Appendix I.

Stage 3

Here one must adjust the polarization state of the receiver to ensure the polarization match, i.e., to receive *all* of the power, contained in the scattered wave.

Such a receiver polarization state is given by⁴:

$$\mathbf{h} = \frac{\mathbf{E}_R^*}{\|\mathbf{E}_R\|} \text{ or } \mathbf{h}_{\text{opt}} = \left\{ \frac{[\mathbf{S}]\mathbf{E}_{T, \text{opt}}}{\|[\mathbf{S}]\mathbf{E}_{T, \text{opt}}\|} \right\}^* \quad (8)$$

where $\|\cdot\|$ indicates the norm. Equation (8) completes the optimization process. We note here that the above procedure *decouples* the transmitter from the receiver maximization, thus reducing two-degree-of-freedom to the two one-degree-of-freedom problems, which is essentially a generalization of the Kennaugh result [2, p. 14] being quoted and discussed in Appendix II.

Probably the most important advantage of this three-stage procedure is the ease with which it can be applied to optimization problems with various constraints.

Indeed, suppose that polarization can only be varied at the receiving end but not at the transmitting end (which may be due, say, to the high power restrictions [21]); it then becomes obvious that stage 1 cannot be executed since \mathbf{E}_T is no longer a variable, and, therefore, the best one can do is to solve for \mathbf{h} in (8) to adjust the receiver. On the other hand, if the situation is reversed for some reason, stage 1 alone must be performed. Next, consider a symmetric, monostatic case where a single antenna acts as both transmitter and the receiver as shown in Fig. 2. Then, as shown in Appendix II, the three-stage procedure can be reduced to the Kennaugh "pseudo-eigenvalue equation":

$$[\mathbf{S}]\mathbf{x} = \mu\mathbf{x}^* \quad (9)$$

which satisfies the requirement of all three stages, when $\mathbf{x} = \mathbf{h} = \mathbf{E}_T$.

Another advantage of the three-stage procedure is the ease with which one can interpret the concept of the so-called co-polarization nulls [2], [6], [14], [15]. Let us define a co-pol null as such a polarization state of a transmitter that the receiving voltage is zero for a given scattering matrix $[\mathbf{S}]$. Mathematically it translates into:

$$[\mathbf{S}]\mathbf{E}_T = \mathbf{E}_R \quad (9a)$$

such that

$$\mathbf{V} = \mathbf{h}^T \mathbf{E}_R = 0. \quad (9b)$$

The last equation is a complete polarization *mismatch* condition and, as such, depends only on stage 3 of the optimization procedure rather than on stage 1 which deals with the reflected energy density optimization. Therefore, the co-pol null computation involves $[\mathbf{S}]$ rather than $[\mathbf{G}]$.

⁴ The reader is reminded that conjugation reverses the sense of rotation of the polarization ellipse, which in turn, accomplishes the polarization match as discussed in Section III.

From (9a) and (9b) one obtains:

$$\mathbf{h}^T [\mathbf{S}] \mathbf{E}_T = \mathbf{h}^T \mathbf{E}_R = 0. \quad (9c)$$

One must note that even for a given $[\mathbf{S}]$, \mathbf{E}_T is not uniquely specified.⁵ The co-pol null does contain additional information about the target (as compared with optimal polarizations defined by (6)–(8)). For instance, in the monostatic case, it gives such a polarization state of the identical receiver/transmitter antennas that the received voltage is zero, *regardless* of the value of the reflected energy.

V. UNITARY CHANGE-OF-BASIS FORMALISM AND TRANSFORMATION PROPERTIES OF THE BASIC EQUATIONS OF RADAR POLARIMETRY

Thus far, we have considered polarimetric optimization problems with all quantities defined in the linear polarization basis, including the discussion of the voltage equation. In practical terms, it means that a set of linearly polarized orthogonal synchronized⁶ antennas is used to resolve any elliptically polarized signal into two components. In applications, however, one may want to use a different (from linearly polarized) set of antennas such as the use of circularly polarized antennas for the measurement of targets in rain,⁷ etc.

Let us consider two radar operators A and B both receiving, say, a horizontally polarized signal. Further, suppose that A uses a HV antenna set and B uses a RHC/LHC antenna set, and therefore, A and B receive the signals $\{\}_1$ and $1/\sqrt{2}\{\}_2$, respectively. How do they compare data? To put it in more general terms, the change-of-polarization-basis formalism is required in order to provide proper comparisons of measurements taken with different antenna sets. The following requirements must be satisfied while changing basis: all measurable quantities such as voltage or energy density etc. must remain invariant under the change-of-basis; orthonormality of any two vectors must be preserved under the change-of-basis. Radar polarimetry operates with two-dimensional polarization states, and therefore the above requirements lead to the use of unitary matrices [18]. The unitary matrices satisfy the requirement $[\mathbf{U}]^T = [\mathbf{U}]^* = [\mathbf{U}]^{-1}$. In the (2×2) complex case, the unitarity requirement imposes four constraints on eight parameters [4]. Hence, $[\mathbf{U}]$ is a function of four variables.⁸

Let us consider the transformation properties of the basic equations (2) and (3) under the unitary change-of-basis transformation $[\mathbf{U}]$. We rewrite them here, for convenience, with $[\mathbf{S}_L]$ indicating that the scattering matrix is measured in a linear polarization basis:

$$\mathbf{E}_R = [\mathbf{S}_L] \mathbf{E}_T \quad (10a)$$

⁵ A geometrical analogy at this point may be helpful. An optimization of the bilinear form (4) is equivalent to finding a peak of a two-dimensional surface, and that is why optimal polarization states (cross-pol nulls) are uniquely defined. The co-pol null, however, involves equating the bilinear form (9) to zero which is, roughly, equivalent to the intersection of a curved surface with a plane where nonuniqueness is apparent.

⁶ By this we mean, essentially, any dual channel polarimeter which is capable of measuring both polarization components coherently.

⁷ In this section, we will restrict ourselves to the monostatic case for conceptual clarity.

⁸ The general unitary matrix must satisfy the $|\det [\mathbf{U}]| = 1$ condition, but not, in general, $\det [\mathbf{U}] = 1$.

$$V = \mathbf{h}^T \mathbf{E}_R = \mathbf{h}^T [S_L] \mathbf{E}_T. \quad (10b)$$

Here, as before, subscripts R and T stand for the received and transmitted wave, respectively, and superscript T denotes the transpose.

Then, under the change-of-basis, the vectors \mathbf{E}_R and \mathbf{E}_T will undergo the inverse transformation [18]

$$\mathbf{E}_R = [U] \mathbf{E}'_R \quad (11a)$$

$$\mathbf{E}_T = [U] \mathbf{E}'_T \quad (11b)$$

$$\mathbf{h} = [U] \mathbf{h}' \quad (11c)$$

where the primes indicate quantities expressed in the new polarization basis.

We then require an obvious physical invariance, namely, that the measured voltage at the receiving antenna terminals be unchanged under the change-of-basis transformation and that the scattering matrix in (10a) connect the same *physical* polarization states as in the old basis.

One then obtains:

$$\begin{aligned} \mathbf{E}_R = [S_L] \mathbf{E}_T &= [U] \mathbf{E}'_R = [S_L] [U] \mathbf{E}'_T = \mathbf{E}'_R \\ &= [U]^{-1} [S_L] [U] \mathbf{E}'_T \end{aligned} \quad (12a)$$

leading to a well-known similarity transformation for a scattering matrix $[S_L]$, i.e.,

$$[S'_L] = [U]^{-1} [S_L] [U] \quad (12b)$$

which ensures invariance of the target operator $[S_{op}]$ properties under the change-of-basis.

Consideration of the voltage equation in an arbitrary elliptical basis gives:

$$V = V' = \mathbf{h}^T \mathbf{E}_R = ([U] \mathbf{h}')^T ([U] \mathbf{E}'_R) = \mathbf{h}'^T [U]^T [U] \mathbf{E}'_R$$

or

$$V' = \mathbf{h}'^T [U]^T [U] \mathbf{E}'_R \quad (13a)$$

instead of (10b).

Note that $[U]^T [U] = [I]$ (identity matrix), if $[U]$ is an orthogonal real matrix, i.e., corresponds to a rotation about the direction of propagation, which means that any linear polarization basis (set of linearly polarized antennas) measures voltage according to (10a), just like a pair of dipoles which is always used in the derivation of (10b). If, however, an elliptical polarization basis is used, (13a) must be used instead, i.e., (10b) is not *covariant* under the change-of-basis (changes its form), whereas, the measured value of V is invariant under the change-of-basis. In summary, we emphasize that the set of equations (10)–(13a) constitutes a complete and sufficient change-of-basis formulation (see "Comments ..." by H. Mieras, *IEEE Trans. Antennas Propagat.*, vol. AP-34, no. 12, pp. 1470–1471, this issue, and our "Authors' Reply ..." *IEEE Trans. Antennas Propagat.*, vol. AP-34, no. 12, pp. 1471–1473, this issue).

However, for an easier comparison with previous treatments [6], [8], [13]–[15], it is instructive to derive another condition, (13b) below, which is equivalent to (13a), and is expressed explicitly in terms of the scattering matrix. We note

the invariance of V gives

$$\begin{aligned} V = V' &= \mathbf{h}^T [S_L] \mathbf{E}_T = ([U] \mathbf{h}')^T [S_L] ([U] \mathbf{E}'_T) \\ &= \mathbf{h}'^T [U]^T [S_L] [U] \mathbf{E}'_T \end{aligned}$$

from which follows:

$$[S'_L] = [U]^T [S_L] [U] \quad (13b)$$

where subscript V indicates that $[S_L]$ in the *voltage* equation is being transformed. We see that (12b) and (13c) are not identical.⁹ As shown in Appendix III

$$[S'_V] = [U]^T [U] [S'_{op}] \quad (13c)$$

and, therefore, (13a) and (13b) are equivalent and interchangeable conditions.

To illustrate the use of (13a) and the difference between $[S'_V]$ and $[S'_L]$, let us consider a problem of a reflection from an infinite, perfectly conducting flat plate at normal incidence (or a large perfectly conducting sphere). Two experimental facts are known to us: the returned wave is in the same polarization *state* as the transmitted one, e.g., changes from RHC to LHC due to reversal in the direction of propagation, and the fact that the voltage developed across the receiving antenna terminals is maximal for linear polarizations and zero for the circular polarizations.

In the linear basis, defined by \hat{x} and \hat{y} units, vector waves polarized along \hat{x} and \hat{y} are given by the $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ -vectors, respectively (up to an absolute phase); circular states by the $1/\sqrt{2} \begin{bmatrix} 1 \\ j \end{bmatrix}$ and $1/\sqrt{2} \begin{bmatrix} 1 \\ -j \end{bmatrix}$ -vectors, respectively, and the scattering matrix $[S_L]$ is given by $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ (up to an overall phase) due to the first experimental fact mentioned above.

Then

$$|V| = V = \left| \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right| = 1 = \max.$$

Next, let us transmit a circularly polarized wave defined in the *same linear basis* so that $[S_L]$ must still be given by

$$[S_L] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

but

$$|V| = V = \frac{1}{2} \left| \begin{bmatrix} 1 & j \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ j \end{bmatrix} \right| = 0 = \min$$

so that the result satisfies experimental facts.

Let us now work out the same problem in the circular polarization basis:

$$(+) \equiv (\hat{x} + j\hat{y})/\sqrt{2}$$

$$(-) \equiv (\hat{x} - j\hat{y})/\sqrt{2},$$

so that

$$[U] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix}^T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$$

⁹ Mathematically, it corresponds to the well-known fact [18, p. 246], [19, pp. 181–182] that linear operators and bilinear forms transform differently under coordinate transformations in any vector spaces, namely, the former undergoes the similarity transformation (13a) and the latter a congruence transformation (13c).

then

$$[S'_{op}(L, R)] = [U]^{-1} [S_L] [U] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

but

$$[S'_v(L, R)] = [U]^T [S_L] [U] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}^T \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

On the other hand, the circular polarization states in their own circular basis are given as they should be by

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \frac{1}{\sqrt{2}} [U]^{-1} \begin{bmatrix} 1 \\ \pm j \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}^* \begin{bmatrix} 1 \\ \pm j \end{bmatrix} \\ = \frac{1}{2} \begin{bmatrix} 1 & -j \\ 1 & \pm j \end{bmatrix} \begin{bmatrix} 1 \\ \pm j \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ and } \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

which gives us the following equations for the \pm states:

$$E'_R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ and } E'_R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

but

$$V' = \left| \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right| = 0$$

again, both results are in agreement with experimental findings.

Notice how $[S'_{op}]$ remained $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ to "keep" the returned waves similar to the transmitted ones, but $[S'_v]$ "shifted" to $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ off-diagonal form to keep the voltage equal to zero for circular polarizations.

Also note that according to (13a), we obtain the following result in a circular basis:

$$V' = \{ \mathbf{h}'^T [U]^T [U] E'_R \} = \left\{ (1 \ 0) \frac{1}{2} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \begin{bmatrix} 1 \\ j \end{bmatrix} \right. \\ \left. \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right\} = \frac{1}{2} \left\{ (1 \ 0) \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right\} = 0$$

again, in agreement with experimental facts.

In our opinion, the aforementioned procedure of using (13a) as compared to (13b) is a more convenient one for practical computations. Namely, once the $[U]$ of a new basis (in terms of a linear polarization basis) is known, the following steps must be performed:

- 1) E'_T must be calculated according to (11b);
- 2) $[S']$ is calculated according to (12b);
- 3) E'_R is computed as $E'_R = [S'] E'_T$;
- 4) V' is determined according to (13a).

Once again, we note that the procedure of using (13a) does not involve $[S_v]$, and therefore does not necessitate the distinction between $[S_{op}]$ and $[S_v]$, but it does enforce the noncovariance of the voltage equation.

VI. SUMMARY

We have tried to concentrate on the foundations of radar polarimetry. Hence, the basic definitions and the main equations were discussed in detail. The basic problem of polarimetric optimization in the radar scattering process was generalized to the case of the nonsymmetric target operator $[S]$ and solved without diagonalizing $[S]$ via the three-stage procedure. Finally, the change-of-basis unitary transformations and properties of the main equations under such transformations were carefully considered. We provided a novel interpretation of the change-of-basis and pointed out noncovariance of the voltage equation. Our goal was to readdress the foundations of the problem and clarify the underlying principles.

APPENDIX I

DETAILS OF THE $[G]$ -EIGENVALUE PROBLEM

According to the Rayleigh principle, an optimization of the quadratic form $\mathbf{x}^T [A] \mathbf{x} / \mathbf{x}^T \mathbf{x}$ leads to an eigenvalue problem $\{[A] - \lambda[I]\} \mathbf{x} = 0$ [18, p. 253]. The same is true for the Hermitian form $\mathbf{x}^* [G] \mathbf{x} / \mathbf{x}^* \mathbf{x}$ [19]. The eigenvalues of a Hermitian matrix are real and the eigenvectors, corresponding to distinct eigenvalues, are orthonormal. The eigenvalues of $[G]$ are invariant under the change-of-basis transformation [18]. Any linear combination of the eigenvalues, such as $\text{tr}\{[G]\}$ or $\det\{[G]\}$ is also an invariant. It can be used to find λ_1 and λ_2 from the following equations:

$$\det\{[G]\} = g_{11}g_{22} - g_{12}g_{21} = \lambda_1 \lambda_2, \quad (14)$$

$$\text{tr}\{[G]\} = g_{11} + g_{22} = \lambda_1 + \lambda_2, \quad (15)$$

whence

$$\lambda_{1,2} = \frac{\text{tr}\{[G]\} \pm (\text{tr}^2\{[G]\} - 4 \det\{[G]\})^{1/2}}{2}. \quad (16)$$

Then, λ_1 and λ_2 can be substituted into (5) in order to solve for the components of $E_{T,opt}^1$. One then obtains:

$$E_{T,opt}^1 = \frac{1}{\{1 + |a|^2\}^{1/2}} \begin{bmatrix} 1 \\ a \end{bmatrix} \quad (17)$$

where $a = \lambda_1 - g_{11}/g_{12}$. The other eigenvector can be found from the orthogonality condition:

$$(E_{T,opt}^1)^* E_{T,opt}^2 = 0.$$

The eigenvalues λ_1 and λ_2 of $[G]$ are related to the eigenvalues μ_1 and μ_2 of $[S]$ by the relations

$$\lambda_1 = |\mu_1|^2; \quad \lambda_2 = |\mu_2|^2. \quad (18)$$

It must be emphasized, however, that eigenvectors of $[S]$ and $[G]$ are, in general, different (unless $[S]$ is normal). It can also be seen from a simple argument that eigenvectors of $[G]$ are

always orthonormal, but eigenvectors of $[S]$ are not, in general, even when $[S]$ is symmetric. Note, however, that the pseudo-eigenvalues of $[S]$, i.e., solutions of (9), are always orthogonal as is shown in Appendix II together with numerical examples. Equation (18) shows that the maximum voltage (echo area) is given by the square of the largest eigenvalue of $[S]$, provided that the polarization match requirements of stage 3 are satisfied. We also note [8] that eigenvectors of $[G]$ will diagonalize $[S]$ via the congruence transformation (13a) without necessarily being the eigenvectors of $[S]$. It may, however, not happen, when a similarity transformation is used. Thus, any physical conclusions based on the diagonal form of $[S]$ must be carefully checked against the meaning of $[S_{op}]$ versus $[S_V]$ for the problem at hand.

APPENDIX II

EIGENVECTORS OF $[G]$ AND $[S]$: RELATION OF THE THREE-STAGE PROCEDURE TO THE KENNAUGH'S "PSEUDO-EIGENVALUE" EQUATION AND SOME NUMERICAL EXAMPLES

Kennaugh [2] used the following equation (see our equation (9) of Section IV) as a polarization match condition for radar backscatter target reception as shown in Fig. 2.

$$[S]x = \mu x^* \quad (19)$$

Furthermore, he concluded that (19) gives the maximum power even for separately varying h and E_T by simply setting $x = h = E_T$ if x satisfies (19). We quote from [2, p. 14]:

"... In either case, transmitting and receiving polarizations are identical for maximum echo area, and the reflected wave is of the polarization which the transmitting antenna best receives. This is an important conclusion. Translated into practical terms, the operator of a radar set using a common transmitting and receiving antenna of variable polarization could adjust the antenna polarization to achieve just as high a return from a fixed radar target as could the operator of a more complicated (and costly) radar with individually variable transmitting and receiving polarizations ..."

In spite of a few very minor mathematical errors, Kennaugh achieved a correct result as we now show.

Indeed, after premultiplying (19) by $[S]^*$, conjugating the result and combining the two equations, (19) can be manipulated into

$$\{[S]^*[S] - |\mu|^2[I]\}x = 0 \quad (20)$$

which is identical with (11), provided $[S]^T = [S]$ and $[S]$ is not singular, because then

$$[G] = [S]^*[S] = [S]^*[S] \text{ and } |\mu|^2 = \lambda.$$

Then one computes $y = [S]x$. Since (19) is identical with (20), $y = [S]x = \mu x^*$. Then it is easy to see that the third-stage equation (8) is also satisfied. Indeed,

$$h = \left\{ \frac{[S]x}{\|[S]x\|} \right\}^* = \left\{ \frac{1}{\|[S]x\|} \mu x^* \right\}^* = \frac{\mu^*}{\|[S]x\|} x$$

which means that polarization states of h and x are identical (up to an absolute phase). Note that if x is a solution of (19) with an eigenvalue μ , then $x' = xe^{i\phi}$ is also a solution with the corresponding eigenvalue $\mu' = \mu e^{2i\phi}$. This means that μ can be chosen to be real. Another way of proving this is the fact that (19) and (20) are identical in a symmetric case and that (20) has real eigenvalues because of Hermiticity. Thus, $h = (\mu/\|[S]x\|)x$ which illuminates the physical meaning of μ , since $\|h\| = \|x\| = 1$, then $\mu = \|[S]x\|$ must be satisfied (i.e., μ is given by the relative power in the reflected wave). Thus Kennaugh's theorem is, indeed, correct which is, in our opinion, another example of the powerful intuition which this great man demonstrated.

The three-stage procedure illuminates the physical meaning of the Kennaugh equation (19), including the origin of μ . Practically speaking, the best way to solve (19) is to manipulate it into (20), since the theory most prevalent is the one for the Hermitian and unitary matrices. Since the condition $[S] = [S]^T$ is so important, we briefly remind the reader of the requirements that need to be satisfied for $[S]$ to be symmetric.

If both the target and the medium satisfy reciprocity properties, then reversal of the trajectory leads to the $[S] \rightarrow [S]^T$ transformation. Further, if the backscatter case is considered, the received power may be the same upon the interchange of the receiver and transmitter which together with the reciprocity condition implies $[S] = [S]^T$. It is worth noticing that the scientific community still owes one a correct and rigorous proof of these widely accepted statements. Thus, when one considers a bistatic case, or when "nonreciprocal" conditions are present, one does not expect $[S]$ to be symmetric. Examples may be a magneto-ionic propagation medium or a target which contains ferromagnetic materials, etc.. Note, that the three-stage procedure will work in the asymmetric case also.

Let us illustrate our findings on eigenvalues and eigenvectors in both the Kennaugh and the three-stage-procedure on the following three examples:

1) Let

$$[S] = \begin{bmatrix} 2j & \frac{1}{2} \\ \frac{1}{2} & -j \end{bmatrix},$$

then (19) or (20) gives

$$[G] = \begin{bmatrix} \frac{17}{4} & -\frac{3}{2}j \\ \frac{3}{2}j & \frac{5}{4} \end{bmatrix},$$

and

$$\lambda_{1,2} = \frac{11 \pm 6\sqrt{2}}{4}.$$

Substituting $\lambda_{1,2}$ in (20) and solving for $E_{T, \text{opt}}$ gives

$$x_1 = \frac{1}{(4 + 2\sqrt{2})^{1/2}} \begin{bmatrix} -j(1 + \sqrt{2}) \\ 1 \end{bmatrix} = E_{T, \text{opt}}$$

$$x_2 = \frac{1}{(4 - 2\sqrt{2})^{1/2}} \begin{bmatrix} -j(1 - \sqrt{2}) \\ 1 \end{bmatrix}$$

Then Kennaugh's equation gives

$$E_{T, \text{opt}} = h = \begin{bmatrix} -0.92j \\ 0.38 \end{bmatrix}$$

and the three-stage-procedure gives the identical $E_{T, \text{opt}}$ and

$$h' = \begin{bmatrix} 0.92 \\ 0.38j \end{bmatrix}$$

Note, that because of $h' = jh$, both procedures agree, i.e., give identical polarization states.

2) Similarly, in the case of $[S] = \begin{bmatrix} j & j \\ j & j \end{bmatrix}$

$$E_{T, \text{opt}} = \begin{bmatrix} 0.49 - 0.74j \\ 0.46 \quad 0j \end{bmatrix} = h$$

and

$$h' = \begin{bmatrix} -0.43 - 0.78j \\ 0.21 - 0.41j \end{bmatrix}$$

Again, h' and h are identical polarization states, since $h' = he^{-j(0.17-2\pi)}$ as a closer examination shows.

3) Next, let us consider an asymmetric example¹⁰

$$[S] = \begin{bmatrix} 2j & \frac{1}{2} \\ 2 & -j \end{bmatrix}$$

The Kennaugh procedure gives

$$E_{T, \text{opt}} = h = \begin{bmatrix} -0.63j \\ 0.77 \end{bmatrix}$$

while the three-stage-procedure predicts

$$E_{T, \text{opt}} = \begin{bmatrix} -0.93j \\ 0.35 \end{bmatrix} \text{ and } h = \begin{bmatrix} 0.68 \\ 0.74j \end{bmatrix}$$

The voltage received in the first case is $|V_1| = 2.62$, and in the second case $|V_2| = 3.02$. Thus, we see that (19) is no longer valid and that the transmitter and receiver have different polarization states.

4) Finally, we would like to give an explicit example (as was promised in the text) of a symmetric $[S]$ such that the eigenvectors of $[S]$ are not orthogonal. Let us solve $[S]x = kx$, rather than the pseudo-eigenvalue (19), for

$$[S] = \begin{bmatrix} 2j & 1/2 \\ 1/2 & -j \end{bmatrix}$$

¹⁰ Of course, Kennaugh devised his approach only for a symmetric case.

and being the same as in example 1). In this case, $k_{1,2} = j/2(1 \pm 2\sqrt{2})$

$$x_1 = \frac{1}{[18 + 12\sqrt{2}]^{1/2}} \begin{bmatrix} (3 + 2\sqrt{2})j \\ 1 \end{bmatrix}$$

$$x_2 = \frac{1}{[18 - 12\sqrt{2}]^{1/2}} \begin{bmatrix} (3 - 2\sqrt{2})j \\ 1 \end{bmatrix}$$

As can be easily seen,

$$x_1^* x_2 = \frac{2}{[(18 + 12\sqrt{2})(18 - 12\sqrt{2})]^{1/2}} \neq 0.$$

It must be emphasized, however, that it is the pseudo-eigenvector of (19) rather than the eigenvectors which corresponds to a cross-pol null. Thus, the cross-pol nulls are always orthogonal.

We note here, to avoid confusion, that real target scattering matrices have elements with the magnitude much less than unity to ensure that the reflected wave power is less than the transmitted wave. In the examples above, the matrices were chosen for convenient computation and the scale factor, $k\{\lambda/(4\pi)^{1/2}r\} \ll 1$, was omitted.

APPENDIX III

DERIVATION OF THE RELATION BETWEEN $[S_{\text{op}}]$ AND $[S_V]$

In any linear basis, $[S_{\text{op}}] = [S_V] = [S_L]$.

Let us use HV as a reference basis, and define by $[U_0]$ a change-of-basis matrix which takes us from HV to a general elliptic basis. Then, according to (9a), (9b)

$$[S_{\text{op}}] = [U_0]^{-1} [S_L] [U_0] \quad (21)$$

$$[S_V] = [U_0]^T [S_L] [U_0]. \quad (22)$$

Premultiplying by $[U_0]$ and postmultiplying by $[U_0]^{-1}$, we obtain

$$[U_0] [S_{\text{op}}] [U_0]^{-1} = [S_L], \quad (23)$$

then substituting for $[S_L]$ from (23) to (22), we finally obtain

$$[S_V] = [U_0]^T [U_0] [S_{\text{op}}]. \quad (24)$$

Note that if $[U_0]^T = [U_0]^{-1}$, then $[S_V] = [S_{\text{op}}]$ which is reasonable since $[U_0]^T = [U_0]^{-1}$ is the orthogonality condition for real matrices which means that $[S_{\text{op}}] = [S_V]$ holds only in a linear (real) polarization basis as it should. For the flat plate example, and a circular basis, we obtain

$$[S_{\text{op}}] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad [U_0] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix}^T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$$

so that

$$[S_V] = \frac{1}{2} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

which agrees with the result of Section IV.

APPENDIX IV

CONSTRUCTION OF THE UNITARY CHANGE-OF-POLARIZATION-BASIS MATRIX

Suppose two orthogonal elliptical polarizations are chosen to form a new polarization basis (i.e., corresponding set of antennas) and are given by the two-dimensional unitary vectors \mathbf{A} and \mathbf{B} . We then write them in terms of *any* linear polarization basis, say, $\mathbf{H}\mathbf{V}$, i.e.,

$$\begin{aligned}\mathbf{A} &= a_{11}\mathbf{H} + a_{12}\mathbf{V} \\ \mathbf{B} &= a_{21}\mathbf{H} + a_{22}\mathbf{V}\end{aligned}\quad (25)$$

or in matrix form

$$\begin{bmatrix} \mathbf{A} \\ \mathbf{B} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \mathbf{H} \\ \mathbf{V} \end{bmatrix} \quad (26)$$

Then the transpose of a_{ij} , i.e., a_{ji} gives the change-of-basis matrix $[U]$ as shown for instance in [19, pp. 118-122].

In the index notation [18, p. 333]:

$$y_j = \sum_{i=1}^2 U_{ij} x_i \quad (27)$$

where $y_1 = \mathbf{A}$, $y_2 = \mathbf{B}$, $x_1 = \mathbf{H}$, and $x_2 = \mathbf{V}$. Taking the transpose of a_{ij} in (26) is equivalent to a summation over the second index in (27). Thus, if

$$(\hat{+}) = \left(\frac{\hat{x} + j\hat{y}}{\sqrt{2}} \right); (\hat{-}) = \left(\frac{\hat{x} - j\hat{y}}{\sqrt{2}} \right)$$

then

$$[U] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}^T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix}.$$

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1986 and "Reduction of bistatic scattering matrix measurements for inversely symmetric radar targets," *IEEE Trans. Antennas Propagat.*, vol. AP-31, no. 2, pp. 237-242, Mar. 1983.)



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Wolfgang-Martin Boerner (S'66-M'67-SM'75-F'84), for a photograph and biography please see page 2 of the January 1984 issue of this TRANSACTIONS.

Comments on "Foundations of Radar Polarimetry"

Harry Mieras

Comments on "On Foundations of Radar Polarimetry"

HARRY MIERAS, SENIOR MEMBER, IEEE

Contained within the above paper¹ is a new convention for polarization scattering matrices. I believe that this new form is ill-advised since it adds unnecessary complication. The criticism here is

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directed only at the new convention (or rather the *interpretation* of certain polarization quantities) and not at the remaining content of the paper; the paper correctly and consistently develops a polarization formalism and points out the need for careful usage of transformation equations. The point of contention is this: the authors distinguish between two forms of scattering matrix S , namely an S_T and an $S_{\theta\rho}$. The appropriate form of S is to be chosen according to whether S appears in a voltage equation or in a polarization-state equation. I object to accepting this because it requires revisiting all existing theory to specify which S was meant where. But this confusion is unnecessary. Only *one* form of S is required. However, it also requires rejecting *one* of the authors' transformation equations and the interpretation of the polarization vector associated with it. I agree with the authors that the choice of convention "is a matter of taste" [1]. A single form of S simplifies theory, not only for the material presented here¹ but also in the further development of polarization theory (e.g., Mueller matrix, covariance matrix [4])—would two forms be required for these as well?

The source of the problem is the physical fact that the sense of elliptical polarization reverses when reflected by a specular scatterer. That is, if left circular polarization is transmitted, the scattered wave will be right circular. When we represent elliptical polarization as a complex two-vector, we cannot avoid introducing a certain amount of awkwardness. The second physical fact is that for specular scattering when the same circularly polarized antenna is used for transmit and receive, the received voltage is null. When a theory is confusing, these two facts can be used to check things out, as is done in the above paper.¹

The fundamental quantities (the things that are measured) are the polarizations of the transmit and receive antennas, \mathbf{E}_T and \mathbf{h} , and the received voltage V . The coordinate systems for \mathbf{E}_T and \mathbf{h} are for convenience chosen attached to the antennas (as also stated in the paper¹) so that if receiver and transmitter are the same, the coordinate systems coincide (the "monostatic convention," see also [2]). With only these definitions we have

$$V = \mathbf{h}^T S \mathbf{E}_T. \quad (1)$$

We now require that V be invariant under a basis (unitary) transformation $U: V' = V$, where $V' = \mathbf{h}'^T S' \mathbf{E}'_T$, $\mathbf{E}'_T = U \mathbf{E}_T$ and $\mathbf{h}' = U \mathbf{h}$. Then we must have

$$S' = U^T S U. \quad (2)$$

This transformation is here claimed to be basic; it is called S_T in (13b) of the paper.¹ The transformation is also so defined and used consistently by Huynen [3], the present writer [4], and indeed in prior work [5] by one of the authors of the paper.¹ Note that contrary to the paper,¹ no statement has been made yet about the scattered vector. Also contrary to the paper,¹ there is no need here to distinguish between linear and other bases when defining S and the equations in which they appear. So far, the development does not disagree with that of the above paper,¹ only here something is left out which then avoids any need for introducing an additional form for S .

Now introduce, if we must, the scattered vector \mathbf{E}_S :

$$\mathbf{E}_S = S \mathbf{E}_T, \quad (3)$$

so that² $V = \mathbf{h}^T \mathbf{E}_S$. Because we consider (1) to be fundamental, it

would be nice if we could also say that in the transformed basis

$$V = V' = \mathbf{h}'^T \mathbf{E}'_S. \quad (4)$$

Substituting from what we have so far, we obtain $\mathbf{h}'^T \mathbf{E}'_S = \mathbf{h}^T (U^{-1})^T \mathbf{E}_S$, or using the property of unitary matrices:

$$\mathbf{E}_S = U \mathbf{E}'_S. \quad (5)$$

(The conjugation reflects the fact that the handedness of the \mathbf{E}_S coordinate system is opposite to that of \mathbf{E}_T .)

This last equation is in direct contradiction with what is found in the paper.¹ It is stated here as a consequence of other definitions. There, \mathbf{E}_S is required to follow the same transformation law as \mathbf{E}_T and then a different equation (3) is derived with $S_{\theta\rho}$ instead of S . Since the present development is simpler, the contention is that (5) should be accepted rather than introducing the new matrix $S_{\theta\rho}$.

Underlying the above disagreement is a difference in the interpretation of the meaning of \mathbf{E}_S . Here, \mathbf{E}_S is considered to be a different kind of thing than \mathbf{E}_T , since their directions of propagation are opposite; hence we should expect that their transformations might be different. In the paper,¹ the direction of propagation is not considered to be part of the meanings of \mathbf{E}_S and \mathbf{E}_T . It is emphasized that both the present development and that of the above paper,¹ are self-consistent. It is also noted that the confusion and awkwardness persist when we treat the problem of multiple scattering. For that, consecutive scattering matrices cannot just be multiplied together, but require that the quantities $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ be interposed [4]. The present arguments are based on convenience. Perhaps the better theoretical approach is to associate a consistently right handed coordinate system with the wave, i.e., for both \mathbf{E}_T and \mathbf{E}_S . This is done in optics and also by Huynen [4]. However, this requires very careful treatment involving several operations of conjugation and multiplication by $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ before we get to V .

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¹ A. B. Kostinski and W. M. Boerner, *IEEE Trans. Antennas Propagat.*, this issue, pp. 1395-1404.

² Here \mathbf{E}_S is used rather than \mathbf{E}_θ as in the paper,¹ to avoid confusion with the receiver.

Authors' Reply

A.B. Kostinski and W-M. Boerner

Authors' Reply by A. B. Kostinski and W.-M. Boerner

This is in reply to the comments by Mieras on our paper. The subject matter has generated a considerable amount of controversy and confusion, and we appreciate the opportunity to address some of

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the issues. First, let us summarize our attitude toward the critique and then proceed to the details.

We agree with our critic about the inconvenience caused by the introduction of the two scattering matrices (the operator and the bilinear form) and we, therefore, reemphasize in this note the fact that this distinction is not necessary in our formalism and was simply included in the paper for completeness of the transformation properties description. We, however, disagree strongly with the method proposed in the comments, of transforming transmitted and received vectors with different unitary matrices, and the second part of this reply is devoted to the detailed explanation of our objections. Several discussions with various workers in the field have demonstrated to us a certain discomfort that many researchers feel about the fact that the voltage equation is not written as a proper inner (Hermitian) product and we, therefore, conclude our reply with the discussion of possible reformulations of the voltage equation and problems associated with it.

As we pointed out in the paper,¹ (discussion following (13a) in the paper and discussion at the end of the specular target illustration), our transformation equations ensure the invariance of the measured value of the voltage under the change of basis but do not guarantee the covariance of the voltage equation; that is to say that the form of the equation depends on the choice of basis according to (13a)¹

$$V' = \mathbf{h}'^T [\mathbf{U}]^T [\mathbf{U}] \mathbf{E}_R' \quad (1)$$

where $[\mathbf{U}]$ is a unitary change-of-basis matrix from a linear polarization reference basis to a given elliptical basis. If the new basis is also a linearly polarized one, the corresponding $[\mathbf{U}]$ is orthogonal (unitary and real) and therefore

$$[\mathbf{U}]^T [\mathbf{U}] = [\mathbf{I}] \quad (2)$$

and

$$V' = \mathbf{h}'^T \mathbf{E}_R' \quad (3)$$

which means "covariance with respect to all linear bases." As we also pointed out in the paper, the transformation (1) together with the scattering operator transformation of (12b)¹

$$[\mathbf{S}'] = [\mathbf{U}]^{-1} [\mathbf{S}] [\mathbf{U}] \quad (4)$$

is completely sufficient for any calculation, it guarantees the invariance of all measured quantities, and avoids the introduction of another form of the scattering matrix! However, we were also aware of the fact that the transformation law of (13b)¹

$$[\mathbf{S}'] = [\mathbf{U}]^T [\mathbf{S}] [\mathbf{U}] \quad (5)$$

is almost always used in the literature [6], [7], [3] and we, therefore, had to show where its use is proper and where it is not. To do that we derived the voltage invariance condition equivalent to (1) in terms of the scattering matrix and the transmitted vector rather than in terms of the reflected one. We obtained (5) as such a condition and noted that $[\mathbf{S}]$ in (5) transforms differently from $[\mathbf{S}]$ in (4) and one then must distinguish between two different forms of $[\mathbf{S}]$ depending on whether one transforms the operator equation

$$\mathbf{E}_R = [\mathbf{S}] \mathbf{E}_T \quad (6)$$

or the voltage bilinear form equation (1). Again, we emphasize that the voltage form of $[\mathbf{S}]$ is not necessary if one takes (1) and (4) as the basic transformation rules, i.e., only the operator form of $[\mathbf{S}]$ is fundamental because (6) is essentially the definition of $[\mathbf{S}]$ and

contains all the information about the scattering process while the voltage equation is the result of the receiving antenna network.

To conclude this section we would like to answer the following natural question: why does the voltage equation "single out" a linearly polarized basis, i.e., why is (1) not covariant with respect to arbitrary unitary $[\mathbf{U}]$? First of all, the voltage equation has always been derived in the linear polarization basis [4]–[6]. Secondly, one must remember that a covariance of a given equation with respect to a wide class of transformations is rather rare. Indeed, consider the analogy of expressing Maxwell's equations in Cartesian and spherical coordinates. Obviously, the form of the equation changes! Another example is Newton's equations which are not covariant with respect to the generalized coordinate transformations which is why Lagrangian mechanics was created [11]. Thus, one should not be disturbed by the fact that the voltage equation in a circular basis is different from the one in a linear basis as long as the physics remains the same.

Let us now consider the transformation rules proposed by Mieras. They are

$$\mathbf{h} = [\mathbf{U}] \mathbf{h}', \quad \mathbf{E}_T = [\mathbf{U}] \mathbf{E}_T', \quad \mathbf{E}_R = [\mathbf{U}^*] \mathbf{E}_R' \quad (7)$$

where the primes indicate the new basis, and the subscript R is used for the reflected wave (rather than subscript s for scattered used by Mieras). Note that the reflected wave polarization state transforms differently from the transmitted one. Since both are measurable quantities they must obey certain invariance properties under the change of basis transformation. In particular, if the two are equal in one basis, they should continue to be equal in another basis regardless of the coordinate system convention used. However, (7) does not obey this requirement because if the two polarization states are equal in one basis and different matrices are used to transform them, they will no longer be equal in the new basis which means that the physics of the scattering process depends on the choice of basis! Indeed, if the scatterer is specular (i.e., "perfect mirror") and (7) is used, one obtains

$$\mathbf{E}_R = \mathbf{E}_T \text{ and } \mathbf{E}_T = [\mathbf{U}] \mathbf{E}_T', \quad \mathbf{E}_R = [\mathbf{U}^*] \mathbf{E}_R' \quad (7a)$$

and one can easily see that in the new basis the transmitted and received polarization states are not equal unless $[\mathbf{U}]$ is real. Is the scatterer not specular in the new basis? Such a conclusion is not acceptable to us because it violates fundamental physical principles.

Let us now continue this note with a few words on a possible alternative formalism. The main source of "inconvenience" of the present treatment is the fact that the voltage equation involves only the transpose of the antenna height \mathbf{h} rather than its Hermitian conjugate. If an extra conjugation of \mathbf{h} would be introduced, then the covariance of the voltage equation would certainly be restored and the two forms of the scattering matrix would transform similarly. How does one make the voltage equation look like a proper inner product? At first glance all one has to do is redefine the antenna height to be the conjugate of what it is now! The situation, in our opinion, is not quite that simple. In order to see it let us come back to the definition and physical meaning of the antenna height. It is defined as the polarization state of the wave transmitted by the antenna in the direction of the target [10]. This definition provides means of measuring the antenna height. The wave which such an antenna best receives in a particular direction is then given by the conjugate of the antenna height in that same direction. This is an experimental fact which is described correctly by the voltage equation (1). Let us now define a new antenna "length" which is the conjugate of the old antenna height. The voltage equation then

becomes

$$V = L^T \cdot E_R = (L, E_R) \quad (8)$$

which is a true inner product and seems, therefore, to be covariant under the unitary change of basis. The problem is, however, in the transformation of L , which is not a measurable quantity but is a "conjugate of a measurable quantity" and one must transform h first to see what transformation applies to L . Thus, it is h which must remain invariant under the change-of-basis transformation (because one measures it) and, therefore, it must transform according to (7). The transformation law for L is computed next as a conjugate of (7) and the result turns out to be equivalent to (1).

It is our opinion that a thorough and careful investigation of the voltage equation from the antenna theory point of view is needed to understand the problem better. In particular, it may be very interesting to repeat the voltage equation derivation directly from Maxwell's equations [10] but in terms of, say, helical antennas rather than a crossed-dipole model.

We now conclude with a reply to several questions raised in the comments concerning the issue of the coordinate system arrangement, definition of the polarization state, and the multiple scattering treatment. Indeed, we do not consider the direction of propagation a part of the polarization state spinor as is explained in Section II of our paper. The reader should note that the polarization ellipse is defined at a fixed point in space [12] and that the same harmonic wave may be linearly polarized at one point and elliptically at another. Since we were interested only in the signal at the receiving antenna terminals the same signal could have come from anywhere in space depending on the target and that is why we prefer to leave the directional information in the exponent as in (1a)-(1c) of the paper.¹ Furthermore, a single coordinate system with its center at the receiving antenna is used because in other conventions the voltage equation must be rederived as is also pointed out by Mieras' comments, and also, because we find dealing with vector products, various parts of which are expressed in different coordinate systems utterly confusing. We believe that the convention similar to ours was often used in optics [13], [14], and especially [15]. We agree totally with Mieras concerning the difficulties of the multiple scattering formalism and a satisfactory solution is yet to be found.

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Extension of Kennaugh's Optimal Polarization Concept to the Asymmetric Scattering Matrix Case

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Abstract—The polarization scattering matrix measured by a bistatic radar system generally will be asymmetric. The scattering matrix will also be asymmetric when the radar system is monostatic, but the intervening propagation medium is anisotropic. Kennaugh's optimal polarizations theory is generalized to the case of the asymmetric scattering matrix. The radar antenna polarizations to be used for maximum and zero power receptions are defined and geometrically interpreted on the Poincaré sphere. These polarizations, termed optimal polarizations, may be used to enhance the level of target echo return, to discriminate against undesired interference sources, or to classify radar targets.

I. INTRODUCTION

A MONOCHROMATIC PLANE wave with a fixed polarization state impinging upon a radar target induces a surface current distribution, which in turn gives rise to a reradiated or scattered field. The polarization state of the wave scattered in the direction of observation will, in general, differ from that of the incident wave. The transformation of the polarization state upon scattering can be represented by a complex scattering matrix, characteristic of the target at a specific aspect and source frequency. The formula used to calculate the target radar cross section or echoing area involves the scattering matrix as well as the transmitting and receiving antenna polarizations. The problem facing the radar operator is the one of selecting the optimal radar polarizations which will, for example, maximize the level of echo signal or minimize the effects of undesired sources, such as clutter return or jamming signals.

Utilizing the principle of electromagnetic reciprocity, one can show that when the radar system is monostatic and the intervening propagation medium is homogeneous and isotropic, the scattering matrix is symmetric. The optimal polarizations associated with a symmetric scattering matrix were first defined by Kennaugh [1] in 1950. In particular, he

found that a copolarized transmitting and receiving radar antenna can be used to obtain the maximum echo return possible, and that there exists only one polarization for which this maximum is achieved. Kennaugh also showed that there are two polarizations for which the backscattered wave is orthogonally polarized to the radar antenna, thus rendering the radar "blind" to the incoming wave.

In a situation where the radar system is bistatic or one in which the target and/or the medium of propagation are anisotropic, the scattering matrix generally will be asymmetric. In this paper, the optimal polarizations theory is generalized to the case of the asymmetric scattering matrix. In particular, it is shown that the maximum echo return can no longer be obtained with an identically polarized transmitting and receiving antenna. The optimal transmitting and receiving antenna polarizations are defined in terms of the scattering matrix elements. It is subsequently proven that for the case of the asymmetric scattering matrix, the copolarized echo return will always be less than the absolute maximum obtained with separately polarized transmitting and receiving antennas. Finally, the optimal polarizations are represented on the Poincaré sphere and certain geometrical properties of the resulting configuration are demonstrated.

II. OVERVIEW AND STATEMENT OF THE PROBLEM

Under the condition that the radar antennas are located sufficiently far from the target, the wave incident on the target and the scattered wave observed at the receiving antenna may be considered to be quasiplanar. In such a case, the electric field vectors E^i and E^s of the incident and the scattered waves,¹ respectively, will lie entirely in the planes perpendicular to the directions of incidence and observation. The standard two-dimensional orthonormal polarization bases may then be used to represent the electric field vectors [2]. Due to the linearity of Maxwell's equations, the components of the vectors E^i and E^s can be related by a 2×2 matrix transformation S as follows:

$$E^s = S \cdot E^i \quad (1)$$

The scattering matrix S serves as a descriptor of the polarizing properties of the target for the particular aspect and frequency of illumination.

The measurable quantity of primary interest to the radar operator is the target radar cross section or echoing area. For a

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¹ Following the convention in [1], [3], the polarization of the scattered wave will be defined as that of the antenna which best receives it.

given incident wave E^i , the echoing area A is a measure of the power density contained in the wave scattered toward the receiver. The echoing area A is calculated according to the following formula:

$$A = 4\pi R^2 \frac{\|S \cdot E^i\|}{\|E^i\|} \quad (2)$$

where $\|\cdot\|$ denotes the norm of the enclosed vector quantity. The norm is defined as $\|E\| = \tilde{E}^* \cdot E$, where the tilde and asterisk denote transposition and conjugation, respectively.

Whenever a mismatch exists between the polarization state of the scattered wave and that of the receiving antenna, only a fraction of the reflected wave's power is sampled. The formula for the resulting effective echoing area must be appropriately redefined to account for the dependence on the receiving antenna polarization. The following bilinear matrix form defines the effective echoing area A_e :

$$A_e = |\tilde{h}' \cdot S \cdot h'|^2 \quad (3)$$

where h' and h' are the normalized ($\|h'\| = \|h'\| = 1$) vector heights of the transmitting and receiving antenna, respectively, [3]. Note, the quantity $A_e = A_e(h', h')$ is a function of two independent variables, namely, h' and h' . The problem analyzed in this paper is that of determining the maxima and minima of A_e and also the corresponding antenna polarizations for which these optimum values of A_e are obtained. Such polarizations are termed optimal.

A special case of expression (3), namely, one in which the transmitting and the receiving antennas are identically polarized ($h' = h' = h$), will be analyzed first. Prior to that, however, it is necessary to consider the definition of identically polarized antennas in the case of a bistatic radar system, since the transmitting and the receiving antenna polarizations are referred to two separate local coordinate systems. Evidently there is no unique way to define co- and cross polarization in the bistatic situation, since several definitions have been offered in the past [4], [5]. However, it is important to note that a unique definition of copolarization is not crucial to the theory presented in this paper. The reason is that the optimal polarizations are physically defined by the radar target itself, and are, therefore, invariant for the various definitions of coordinate systems. In other words, even though the mathematical expressions representing the optimal polarizations may change depending on the particular choice of the reference coordinate system, the physical attributes of the optimal polarizations, such as ellipticity, sense of rotation, and the orientation angle (referred to the plane defined by the directions of incidence and observation), remain invariant.

Returning to expression (3) and setting $h' = h' = h$ yields the following quadratic matrix form

$$A_e = |\tilde{h} \cdot S \cdot h|^2 \quad (4)$$

The scattering matrix S appearing in (4) will be asymmetric in general. From elementary matrix theory it is known that any asymmetric matrix can be decomposed into a symmetric (S_s)

and a skew-symmetric (S_a) component as follows:

$$S_s = (S + \tilde{S})/2 \quad (5a)$$

$$S_a = (S - \tilde{S})/2 \quad (5b)$$

The value of the quadratic form defined by (4) remains unchanged if the matrix S is replaced by its symmetric component S_s .

The problem of finding the optimal polarizations for an asymmetric matrix S will be divided into two parts. In the first part, the properties of scattering matrices will be investigated under the restriction of identically polarized transmitting and receiving antennas. From the concluding sentence of the previous paragraph it is seen that, in this case, only the symmetric component of the scattering matrix need be considered. In the second part, the restriction will be removed and a more general problem of the asymmetric scattering matrix and separately polarized radar antennas will be considered.

III. POLARIZATION BASIS TRANSFORMATIONS

Transformation of polarization vectors from one orthonormal basis to another is accomplished through the use of unitary matrices. Unitary basis transformations have the important property of preserving the total power in the wave [2], i.e., the norm of the electric field vector ($\|E\|$) is invariant under unitary transformations. A unitary transformation matrix T must satisfy the following conditions:

$$|\det \{T\}| = 1 \quad (6a)$$

$$T^{-1} = \tilde{T}^* \quad (6b)$$

The most general form of a unitary matrix, satisfying (6a) and (6b), is given by

$$T = \begin{bmatrix} e^{j\psi_1} \cos(\gamma/2) & -e^{j\psi_2} \sin(\gamma/2) \\ e^{j\psi_3} \sin(\gamma/2) & e^{j\psi_4} \cos(\gamma/2) \end{bmatrix} \quad (7)$$

where, because of condition (6a), the phases of the matrix elements are interrelated as follows: $\psi_1 + \psi_4 = \psi_2 + \psi_3$. Without any loss of generality the following choices may be made: $\psi_1 = \psi_4 = 0$ and $\psi_3 = -\psi_2 = \delta$, in which case the matrix T will take on the following form [6], [7]:

$$T = \begin{bmatrix} \cos(\gamma/2) & -e^{j\delta} \sin(\gamma/2) \\ e^{j\delta} \sin(\gamma/2) & \cos(\gamma/2) \end{bmatrix} \\ = \frac{1}{(1 + \rho\rho^*)^{1/2}} \begin{bmatrix} 1 & -\rho^* \\ \rho & 1 \end{bmatrix} \quad (8)$$

where $\rho = \tan(\gamma/2)e^{j\delta}$.

The particular explicit form of T given in (7) and (8) was chosen because of its intimate connection to the geometrical representation of unitary transformations on the Poincaré sphere. In fact, when the Poincaré sphere is used to represent two orthonormal bases, namely, $\{e_1, e_2\}$ and $\{e_H, e_V\}$, the geometrical transformation analogous to (8) is accomplished using the angles γ and δ as shown in Fig. 1.

Utilizing the transformation matrix defined in (8), the

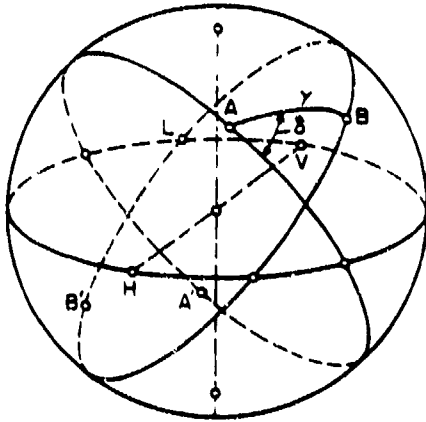


Fig. 1. Polarization basis transformation on the Poincaré sphere.

vectors E' , E^s can be transformed from the $[e_A, e_{A'}]$ basis into the $[e_B, e_{B'}]$ basis in the following manner:

$$E'(A, A') = T \cdot E'(B, B') \quad (9a)$$

$$E^s(A, A') = T^* \cdot E^s(B, B'). \quad (9b)$$

Note that the incident and the scattered waves are propagating in opposite directions. Consequently, in order for the transformation to have the same effect on the polarization state of E' and E^s , the matrices used to transform E' and E^s must be related through conjugation [2], [6]. The latter fact is reflected in relations (9a) and (9b).

Recalling that the relation between $E'(A, A')$ and $E^s(A, A')$ is given by

$$E^s(A, A') = S(A, A') \cdot E'(A, A'), \quad (10)$$

and substituting the relations in (9a), and (9b) into (10) yields the scattering matrix representation in the $[e_B, e_{B'}]$ basis, the resulting expression is given by

$$S(B, B') = \tilde{T} \cdot S(A, A') \cdot T. \quad (11)$$

The general situation is conveniently summarized in the following diagram:

$$\begin{array}{ccccc} E'(B, B') & \xrightarrow{S(B, B')} & E^s(B, B') & & \\ T \downarrow & & \downarrow T^* & & \\ E'(A, A') & \xrightarrow{S(A, A')} & E^s(A, A') & & \end{array}$$

Finally, it is proven that the type of transformation prescribed by Equation (11) preserves the (skew-) symmetry of a matrix. Starting with a symmetric matrix S , or a skew-symmetric matrix S_s and applying the transformation yields

$$\tilde{T} \cdot S_{s,a} \cdot T = S'_{s,a}. \quad (12)$$

Taking note of the fact that $S'_{s,a} = \pm S_{s,a}$, leads to the

following equation:

$$\begin{aligned} S'_{s,a} &= (\tilde{T} \cdot S_{s,a} \cdot T) = \tilde{T} \cdot S_{s,a} \cdot T \\ &= \pm (\tilde{T} \cdot S_{s,a} \cdot T) = \pm S'_{s,a} \end{aligned} \quad (13)$$

where the lower sign corresponds to the second subscript.

IV. OPTIMAL POLARIZATIONS ASSOCIATED WITH A SYMMETRIC SCATTERING MATRIX

Consider a situation wherein the scattering matrix, obtained either through measurement or theoretical computation, is represented in an orthonormal basis $[e_A, e_{A'}]$ by a complex asymmetric matrix $S(A, A')$. The effective echoing area obtained by transmitting and receiving with the same polarization $h(A, A')$ ($\|h(A, A')\| = 1$) is given by

$$\begin{aligned} A_e &= |\tilde{h}(A, A') \cdot S(A, A') \cdot h(A, A')|^2 \\ &= |\tilde{h}(A, A') \cdot S_s(A, A') \cdot h(A, A')|^2 \end{aligned} \quad (14)$$

where the matrix $S(A, A')$ has been replaced by its symmetric component $S_s(A, A')$. Note, no loss in generality occurs if the matrix $S(A, A')$ is symmetric from the outset.

Optimization of the quadratic form for A_e is simplified by finding a basis in which the scattering matrix is diagonal. The type of basis transformation described in Section III can be used to diagonalize a complex symmetric matrix [2], [9]. There remains, however, the problem of finding the actual transformation matrix T_M , satisfying the relation

$$\tilde{T}_M \cdot S(A, A') \cdot T_M = S_d(M, M') \quad (15)$$

where $S_d(M, M')$ is a complex diagonal matrix. Premultiplying both sides of (15) by the respective conjugates yields the following expression:

$$\begin{aligned} \tilde{T}_M^* \cdot P(A, A') \cdot T_M &= T_M^{-1} \\ &\cdot P(A, A') \cdot T_M = P_d(M, M') \end{aligned} \quad (16)$$

where $P(A, A') = S_s^*(A, A') \cdot S_s(A, A')$ and $P_d(M, M') = S_d^*(M, M') \cdot S_d(M, M')$. The matrices $P(A, A')$ and $P_d(M, M')$ are known as power scattering matrices [2]. Note, the diagonal elements of $P_d(M, M')$ are the eigenvalues of $P(A, A')$ and are equal to the squared magnitudes of the respective elements of $S_d(M, M')$. The basis $\{h_M, h_{M'}\}$ consists of the eigenvectors of $P(A, A')$ and will, therefore, be termed the "characteristic" basis. It can be proven that such a basis is orthogonal [8]. Moreover, Kennaugh has shown [1] that the maximum value of A_e is equal to the larger eigenvalue of $P(A, A')$ and the "maximum" polarization is the corresponding eigenvector.

The eigenvalues of $P(A, A')$ are found in the usual manner, i.e., by solving the equation

$$\det \{P(A, A') - |\lambda|^2 I\} = 0. \quad (17)$$

The particular values of $|\lambda|^2$ satisfying this equation are given by

$$|\lambda_{1,2}|^2 = \frac{\text{tr} \{P(A, A')\} \pm \sqrt{\text{tr}^2 \{P(A, A')\} - 4 \det \{P(A, A')\}}}{2} \quad (18)$$

where $\lambda_{1,2}$ are the complex diagonal elements of $S_d(M, M')$. It is interesting to note that $\text{tr} \{P(A, A')\} = \text{tr} \{P(M, M')\}$ and $\det \{P(A, A')\} = \det \{P(M, M')\}$, i.e., the trace and the determinant are invariant under the unitary basis transformation. Furthermore, it can be shown that

$$\text{tr} \{P(A, A')\} = \text{span} \{S_d(A, A')\} \quad (19a)$$

and

$$\det \{P(A, A')\} = |\det \{S_d(A, A')\}|^2 \quad (19b)$$

where the span of a complex matrix is defined as the sum of the squared magnitudes of its elements.

The transformation matrix T_M and the eigenvectors $h_M, h_{M'}$ corresponding to $|\lambda_{1,2}|^2$ are found by substituting $|\lambda_{1,2}|^2$ into (17). The result is given by

$$h_M = C_M \begin{bmatrix} 1 \\ \rho_M \end{bmatrix}; \quad h_{M'} = C_M \begin{bmatrix} -\rho_M^* \\ 1 \end{bmatrix} \quad (20)$$

and

$$T_M = C_M \begin{bmatrix} 1 & -\rho_M^* \\ \rho_M & 1 \end{bmatrix} \quad (21)$$

where

$$\rho_M = \frac{|\lambda_1|^2 - P_{AA'}}{P_{AA'}}; \quad C_M = \frac{1}{\sqrt{1 + \rho_M \rho_M^*}} \quad (22)$$

and $P_{AA}, P_{AA'}$ are the elements of the power scattering matrix $P(A, A')$.

From (17) it is clear that $|\lambda_1|^2 \geq |\lambda_2|^2$. Therefore, $A_{e,\max} = |\lambda_1|^2$ and the maximum polarization is given by h_M .

Another type of optimum polarization which finds use, namely, the "null" polarization, is defined by the condition $A_e = 0$. In deriving the "null" polarizations, it is convenient to use the following expression for A_e :

$$A_e = |\tilde{h}(M, M') \cdot S_d(M, M') \cdot h(M, M')|^2 \quad (23)$$

where $S_d(M, M')$ is found by substituting (21) into (15). Setting (23) equal to zero yields the following result:

$$\tilde{h}_0(M, M') \cdot S_d(M, M') \cdot h_0(M, M') = 0. \quad (24)$$

Two "null" polarizations generally will be found by expanding (24). The polarization ratios defining the "null" polarizations are given by [1]

$$\begin{aligned} \rho_{1,2} &= \pm j \sqrt{\frac{S_{MM}}{S_{M'M'}}} = \sqrt{\frac{|S_{MM}|}{|S_{M'M'}|}} \\ &\cdot \exp \left[j \left(\frac{\phi_{MM} - \phi_{M'M'}}{2} \right) \pm j \frac{\pi}{2} \right] \\ &= \tan \left(\frac{\gamma_{1,2}}{2} \right) \exp [j\delta_{1,2}]. \end{aligned} \quad (25)$$

As (25) indicates, the magnitudes of the polarization ratios $\rho_{1,2}$ are equal, i.e., $\gamma_1 = \gamma_2 = \gamma$, and the phase difference δ_1

– δ_2 is equal to π . An interesting geometrical interpretation of these facts is as follows.

Let the orthonormal basis $\{h_M, h_{M'}\}$ be represented on the Poincaré sphere by antipodal points, M, M' , as shown in Fig. 2. According to the Poincaré sphere rules [9], [10], [11], all polarizations with equivalent polarization ratio magnitudes lie on a small circle, centered on the diameter joining M and M' . Change in the phase of the polarization ratio, on the other hand, rotates the point representing the polarization about the diameter MM' . When the stated rules are used to map the "null" polarizations $N_{1,2}$ on the Poincaré sphere, the following observations are made. Since the difference in the rotations of the points N_1, N_2 about MM' is equal to π , they are located on the same great circle. Moreover, the fact that $\gamma_1 = \gamma_2 = \gamma$ implies that the angle $N_1 ON_2$ (O is the center of the sphere) is bisected by MM' . These conclusions are illustrated in Fig. 2.

V. OPTIMAL POLARIZATIONS ASSOCIATED WITH THE ASYMMETRIC SCATTERING MATRIX

In the preceding section the radar system was constrained to transmit and receive with the same polarization. In this section, the restriction is dropped, and distinct transmitting and receiving antenna polarizations, which maximize A_e , are found.

Initially, the asymmetric scattering matrix $S(A, A')$ is transformed into the "characteristic" basis $\{h_M, h_{M'}\}$. It was demonstrated in Section IV that this transformation diagonalizes the symmetric component of $S(A, A')$. In addition, it was proven in Section III that this type of transformation preserves the skew-symmetry of $S_a(A, A')$. Therefore, the transformed matrix $S(M, M')$ can be expressed as a sum of a diagonal and a skew-symmetric matrix, i.e.,

$$\begin{aligned} S(M, M') &= \tilde{T}_M \cdot S(A, A') \cdot T_M \\ &= \tilde{T}_M \cdot S_t(A, A') \cdot T_M + \tilde{T}_M \cdot S_a(A, A') \cdot T_M \\ &= S_d(M, M') + S_a(M, M') \\ &= \begin{bmatrix} S_{MM} & S_{MM'} \\ -S_{MM'} & S_{M'M'} \end{bmatrix}. \end{aligned} \quad (26)$$

Next, the problem of determining the polarizations $h'(M, M')$ which maximize A_e , is considered. The following formula will be used to express A_e .

$$A_e = |\tilde{h}'(M, M') \cdot S(M, M') \cdot h'(M, M')|^2. \quad (27)$$

Again, just as in the case of the symmetric scattering matrix, diagonalization of the matrix will facilitate the mathematical procedure used to maximize the bilinear form in (27). It is well known that an asymmetric complex matrix cannot be diagonalized by the type of basis transformation defined in Section III. However, the asymmetric matrix $S(M, M')$ can be diagonalized by two distinct transformation matrices T_I and T_R used in the following manner [12]:

$$\tilde{T}_R \cdot S(M, M') \cdot T_I = S_d(R; I). \quad (28)$$

Equation (28) describes a mixed basis transformation, i.e., one in which the incident and scattered polarizations are

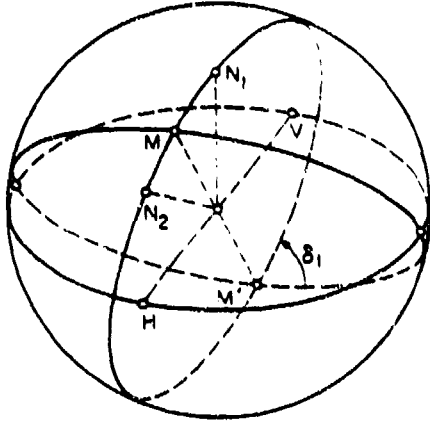


Fig. 2. Optimal polarization configuration for a symmetric scattering matrix.

transformed into two distinct bases, namely, $\{e_I, e_{I'}\}$ and $\{e_R, e_{R'}\}$, respectively.

When the formula for A_e is rewritten in the following fashion.

$$A_e = |\tilde{h}'(R, R') \cdot S_d(R; I) \cdot h'(I, I')|^2, \quad (29)$$

it can be shown that the maximum value of A_e is equal to the squared magnitude of that element of $S_d(R; I)$ which has the larger absolute value. The antenna polarizations for which this maximum is obtained are given by either $h' = e_R, h' = e_I$ or $h' = e_{R'}, h' = e_{I'}$, depending upon which matrix element has the greater absolute value. The explicit representation of the optimal polarizations $h^{I'}$ will be found next.

Conjugating and transposing (28) yields

$$T_I^* \cdot \tilde{S}^*(M, M') \cdot T_R^* = \tilde{S}_d^*(R; I). \quad (30)$$

Now, premultiplying both sides of (28) by the corresponding sides of (30) in one case, and postmultiplying in another, reduce the problem of finding T_I, T_R to two problems of the type solved in Section IV. The equations resulting from the prescribed operations are given by

$$T_I^{-1} \cdot P(M, M') \cdot T_I = P_d(R; I) \quad (31a)$$

$$T_R^* \cdot P'(M, M') \cdot T_R^* = P_d(R; I) \quad (31b)$$

where

$$P(M, M') = \tilde{S}^*(M, M') \cdot S(M, M');$$

$$P'(M, M') = S(M, M') \cdot \tilde{S}^*(M, M');$$

$$P_d(R; I) = \tilde{S}_d^*(R; I) \cdot S_d(R; I).$$

The nonzero elements of $P_d(R; I)$ are the eigenvalues of both $P(M, M')$ and $P'(M, M')$. The bases $\{e_I, e_{I'}\}$ and $\{e_R, e_{R'}\}$ consist of the eigenvectors of $P(M, M')$ and $P'(M, M')$, respectively. Following the procedure used in the preceding section, the following results are obtained:

$$|\mu_{1,2}|^2 = \frac{\text{tr} \{P\} \pm \sqrt{\text{tr}^2 \{P\} - 4 \det \{P\}}}{2} \quad (32)$$

where $\mu_{1,2}$ are the diagonal elements of $S_d(R; I)$ and P stands for either $P(M, M')$ or $P'(M, M')$;

$$\rho_I = \frac{|\mu_1|^2 - P_{MM'}}{P_{MM'}}; \quad (33a)$$

$$\rho_R = \left(\frac{|\mu_1|^2 - P'_{MM'}}{P'_{MM'}} \right)^* \quad (33b)$$

where $P_{MM}, P_{MM'}$ are the elements of $P(M, M')$ and $P'_{MM}, P'_{MM'}$ are the elements of $P'(M, M')$,

$$e_I = C_I \begin{bmatrix} 1 \\ \rho_I \end{bmatrix}; \quad e_{I'} = C_I \begin{bmatrix} -\rho_I^* \\ 1 \end{bmatrix};$$

$$T_I = C_I \begin{bmatrix} 1 & -\rho_I^* \\ \rho_I & 1 \end{bmatrix} \quad (34)$$

$$e_R = C_R \begin{bmatrix} 1 \\ \rho_R \end{bmatrix}; \quad e_{R'} = C_R \begin{bmatrix} 1 \\ \rho_R \end{bmatrix};$$

$$T_R = C_R \begin{bmatrix} 1 & -\rho_R^* \\ \rho_R & 1 \end{bmatrix} \quad (35)$$

and

$$C_{I,R} = \frac{1}{\sqrt{1 + \rho_{I,R} \cdot \rho_{I,R}^*}}.$$

From (32) it is clear that $|\mu_1|^2 \geq |\mu_2|^2$ and, therefore, $A_{e,\max} = |\mu_1|^2$. The corresponding optimal polarizations are $h' = e_I, h' = e_R$.

In Section IV it was demonstrated that when the radar was constrained to transmit and receive with the same polarization, the maximum echo area obtainable was given by $A_{e,\max} = |S_{MM}|^2 = |\lambda_1|^2$. In this section it was shown that by using distinctly polarized transmitting and receiving antennas, the maximum echoing area $A_{e,\max} = |\mu_1|^2$ was obtained. In what follows it is proven that $|\mu_1|^2$ is the absolute maximum of the function $A_e(h', h')$, exceeding the value of $|\lambda_1|^2$. The proof utilizes the fact that the trace and the determinant of the power scattering matrix are invariant under all unitary basis transformations, i.e.,

$$\begin{aligned} \text{tr} \{P_d(R; I)\} &= |\mu_1|^2 + |\mu_2|^2 = \text{tr} \{P(M, M')\} \\ &= |\lambda_1|^2 + |\lambda_2|^2 + 2|S_{MM'}|^2 \end{aligned} \quad (36)$$

and

$$\begin{aligned} \det \{P_d(R; I)\} &= |\mu_1|^2 |\mu_2|^2 = \det \{P(M, M')\} \\ &= |\lambda_1|^2 |\lambda_2|^2 + |S_{MM'}|^4 \\ &\quad + 2|\lambda_1| |\lambda_2| |S_{MM'}|^2 \cdot \cos \alpha \end{aligned} \quad (37)$$

where $\lambda_1 = S_{MM}, \lambda_2 = S_{M'M'}$, and $\alpha = \phi_{MM} + \phi_{M'M'} - 2\phi_{MM'}$.

From (36) and (37) it follows that

$$\begin{aligned} (|\mu_1|^2 - |\mu_2|^2)^2 &= (|\lambda_1|^2 - |\lambda_2|^2)^2 \\ &\quad + 4|S_{MM'}|^2 (|\lambda_1|^2 + |\lambda_2|^2 - 2|\lambda_1| |\lambda_2| \cos \alpha) \end{aligned} \quad (38)$$

and, consequently,

$$(|\mu_1|^2 - |\mu_2|^2)^2 \geq (|\lambda_1|^2 - |\lambda_2|^2)^2. \quad (39)$$

From (36) and (39) the following set of inequalities is obtained

$$\left. \begin{aligned} |\mu_1|^2 + |\mu_2|^2 &\geq |\lambda_1|^2 + |\lambda_2|^2 \\ |\mu_1|^2 - |\mu_2|^2 &\geq |\lambda_1|^2 - |\lambda_2|^2 \end{aligned} \right\} |\mu_1|^2 \geq |\lambda_1|^2, \quad (40)$$

which yield the proof of the fact that $|\mu_1|^2 \geq |\lambda_1|^2$.

Finally, the "maximum" polarizations $\mathbf{h}' = \mathbf{e}_I$, $\mathbf{h}'' = \mathbf{e}_R$ are represented on the Poincaré sphere. The polarization ratios corresponding to \mathbf{h}' and \mathbf{h}'' are given by

$$\rho' = \rho_I = \tan\left(\frac{\xi_I}{2}\right) e^{j\delta_I} \quad (41a)$$

$$\rho'' = \rho_R = \tan\left(\frac{\xi_R}{2}\right) e^{j\delta_R}. \quad (41b)$$

Taking note of the fact that $P'_{MM} = P_{MM}$ and $P'_{MM'} = -P_{MM'}$ and using (33a) and (33b), ρ' and ρ'' may be related as follows:

$$\rho' / \rho'' = \frac{|\mu_1|^2 - P_{MM}}{P_{MM'}} \cdot \frac{-P_{MM'}}{|\mu_1|^2 - P_{MM}} = -1. \quad (42)$$

The implications of the above result are that $\xi_R = \xi_I = \xi$ and $\delta_R - \delta_I = \pi$. According to the Poincaré sphere rules expounded at the end of the preceding section, the optimal polarizations \mathbf{h}' represented by points I , S , respectively (Fig. 3), are located on the same great circle and the angle IOS is bisected by the diameter MM' .

Furthermore, it can be shown that the angle β included between the planes of the great circles containing N_1 , N_2 , and I , S is given by

$$\beta = \arccot \left\{ \frac{|\lambda_1| + |\lambda_2|}{|\lambda_1| - |\lambda_2|} \right\} \tan \nu \quad (43)$$

where $\nu = \phi_{MM'} - (1/2)(\phi_{MM} + \phi_{M'M'})$.

The complete optimal polarizations configuration on the Poincaré sphere is illustrated in Fig. 3.

VI. DISCUSSION AND CONCLUSION

The optimal polarizations of the scattering matrix were derived for the general asymmetric case. The approach followed in this paper is based on the detailed expositions given in [13] and consisted of several steps. In Section IV, the optimal polarizations were derived for the case when the radar antennas are constrained to transmit and receive with the same polarization. In the next section, the restriction on the radar antennas was dropped and the optimal polarizations were obtained in the most general case. Several basis transformations were undertaken in the course of deriving the final result. These transformations were performed in order to facilitate the geometrical interpretation of the optimal polarizations on the Poincaré sphere. The final results can be obtained by circumventing the transformations and applying (33)–(35) in the original basis.

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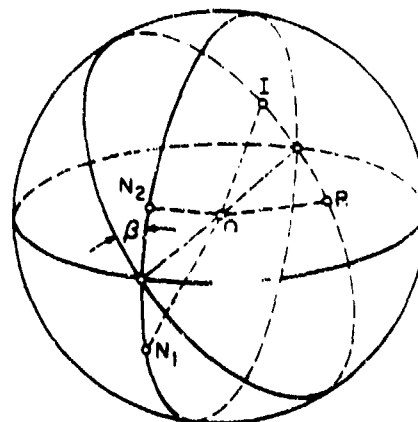


Fig. 3. Optimal polarization configuration for an asymmetric scattering matrix.

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Marat Davidovitz (S'81), for a photograph and biography please see page 242 of the March 1983 issue of this TRANSACTIONS.

Wolfgang-Martin Boerner (S'66–M'67–SM'75–F'84), for a photograph and biography please see page 2 of the January 1984 issue of this TRANSACTIONS.

Interpretation of the Polarimetric Co-polarization Phase Term in Radar Images Obtained with the JPL Airborne *L*-Band SAR System

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Interpretation of the Polarimetric Co-polarization Phase Term in Radar Images Obtained with the JPL Airborne L-Band SAR System

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Abstract—The utilization of both polarimetric amplitude and relative phase terms of the polarization scattering matrix $[S]$, given for each pixel, is pursued for polarimetric SAR imagery interpretation. The existing amplitude-only backscattering approaches hitherto used are extended and modified to accommodate the interpretation of information contained in the amplitude and/or phase terms. Both a vector radiative transfer model for surface versus volume scattering from rough terrain with and without vegetation canopy and a high-frequency electrical curvature model for perfectly conducting surfaces are examined to come up with theoretical models that out-perform other hitherto known approaches. The developed models agree with the excellent polarimetric SAR imagery recently obtained with the JPL CV-990 dual-polarization L-band (1.225 GHz) SAR system. Recommendations are made on how to further perfect the system for integration in the SIR-C and other future polarimetric SIR-SAR systems.

I. INTRODUCTION

HITHERTO, SAR images of terrain and/or sea surfaces have been obtained using amplitude-only measurements (RCS) of selected components S_{HH} , S_{VV} , S_{HV} , S_{VH} of the radar scattering matrix $[S]$ and more recently also its incoherent superposition ($\text{Span } [S] = |S_{HH}|^2 + |S_{VV}|^2 + 2|S_{HV}|^2$) [1]. As was demonstrated in recent workshop contributions and publications of Boerner *et al.* [2], [3], considerable progress was made in vector diffraction, scattering, and radiative transfer theory, as well as in radar polarimetry regarding the implementation of polarimetric amplitude and phase information into SAR imagery. The resulting polarimetric SAR imaging techniques provide increased resolution and quality of SAR imagery as will be demonstrated in the following. By inspection of the excellent results recently obtained [4]¹ on multi-polarization SAR imagery, it was demonstrated that in addition to processing the span of the pixel matrix ($\text{Span } [S]$), also the relative co-polarization phase term ($\phi_{HH} - \phi_{VV}$) provides excellent, similar, and new information useful for terrain, sea surface, and volumetric scatter interpretation. As was shown recently by Foo *et al.* [5] in

the vector extension of the "physical optics current approximation to generally curved surfaces," this relative co-polarization phase term ($\phi_{HH} - \phi_{VV}$) of the monostatic RCS matrix $[S]$ can be related to the difference in electric curvature $[(K_u - K_v)/k]$ at the specular point of a perfectly conducting smooth convex scatterer as

$$\left(\frac{\phi_{HH} - \phi_{VV}}{2}\right) = \pm \arctan\left(\frac{K_u - K_v}{2k}\right). \quad (1)$$

This term suggests that whenever we are dealing with an electrically flat surface, the relative co-polarization phase in the backscattering direction approaches zero, whereas for a highly electrically curved surface it approaches 180° provided look angles are near nadir. In the following, we will show how this formula can be used for the interpretation of JPL polarimetric amplitude and/or phase imagery for look angles close to nadir. For look angles increasingly off nadir and toward grazing angles, the above phase-curvature approach leading to (1) cannot be applied, and another interpretation of the relative co-polarization phase ($\phi_{HH} - \phi_{VV}$) is required that can accommodate multipath phase difference contributions. Such co-polarization phase differences result from multibounce effects along vegetated, smooth, or rough terrain and from pronounced atmo/tropospheric layers.

In order to explain our findings, the underlying theory is briefly sketched in Section II. In Section III, the pertinent results of vector radiative transfer are reviewed, whereas in Section IV, a detailed interpretation of the JPL polarimetric SAR imagery using our formula is given, and finally in Section V, we provide recommendations for further perfection of polarimetric high-resolution SAR measurement and processing systems.

II. FIRST-ORDER CORRECTION TO PHYSICAL OPTICS SCATTERING

For a perfectly conducting target, the far scattered field \vec{H}_s can be expressed in terms of the current induced on the target surface due to incident field [6]

$$r\vec{H}_s(\vec{r}, t) = \frac{1}{4\pi} \iint \left\{ \frac{\partial}{\partial \tau} \vec{J}(\vec{r}', \tau) \right\} \times \hat{a}_r ds' \quad (2)$$

where \vec{J} denotes the induced surface current density, \vec{r} and \vec{r}' denote position vectors to the observation point

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¹Also see N. Donovan, D. Evans, and D. Held, Eds., *NASA/JPL Aircraft SAR Workshop Proc.* (JPL, Pasadena, CA, Feb. 4-5, 1985), JPL Pub. 85-39, June 15, 1985.

and integration point, respectively. \hat{a}_i denotes the unit vector of \vec{r} , and τ is the retarded time.

A space-time integral equation derived by Bennett *et al.* [6] enables $\vec{J} = \vec{J}_{po} + \vec{J}_e$ to be written as a sum of physical optics currents \vec{J}_{po} and contribution of retarded currents \vec{J}_e for the illuminated side, where

$$\vec{J}_{po} = 2\hat{a}_n \times \vec{H}_i \quad (3)$$

and

$$\vec{J}_e = \{ \hat{a}_u J_u - \hat{a}_v J_v \} \frac{K_u - K_v}{4} \epsilon_0 \quad (4)$$

\hat{a}_n denotes the outward normal vector, \hat{a}_u and \hat{a}_v denote unit vectors along the principal directions with curvatures K_u and K_v , and J_u and J_v are the components of \vec{J} along \hat{a}_u and \hat{a}_v , respectively, as shown in Fig. 1. Equation (4) is a first-order approximation derived [6] from integrating over a small specular patch of radius ϵ_0 . Discussion here is restricted to the illuminated side of a smooth, conducting, and convex target. By assuming physical optics currents for J_u and J_v in (4) and then substituting (3) and (4) into (2), the total impulse response of the far scattered field \vec{H}_s due to both \vec{J}_{po} and \vec{J}_e can be obtained [6], [5]

$$r\vec{H}_s(\vec{r}, t) = \frac{1}{2\pi} \frac{\partial^2}{\partial t^2} A(t) \hat{a}_{Hi} + \frac{K_u - K_v}{4\pi} \frac{\partial A(t)}{\partial t} \cdot \{ (\hat{a}_{Hi} \cdot \hat{a}_u) \hat{a}_u - (\hat{a}_{Hi} \cdot \hat{a}_v) \hat{a}_v \} \quad (5)$$

where \hat{a}_{Hi} is the unit vector along the incident field \vec{H}_i (Fig. 1), and $A(t)$ is the silhouette area of the target as delineated by the wavefront moving at half light speed. Taking the Fourier transform of (5), expressions for the scattering matrix components can be obtained [5]

$$S_{11} = \frac{1}{2\pi} (jk)^2 A(k) - (jk) A(k) \frac{K_u - K_v}{4\pi} \cos 2\alpha \quad (6)$$

$$S_{22} = \frac{1}{2\pi} (jk)^2 A(k) + (jk) A(k) \frac{K_u - K_v}{4\pi} \cos 2\alpha \quad (7)$$

$$S_{21} = (jk) A(k) \frac{K_u - K_v}{4\pi} \sin 2\alpha = S_{12} \quad (8)$$

where $A(k)$ is the Fourier transform of $A(t)$, k is the wave number, and α is the polarization angle between \vec{H}_i and \hat{a}_u (Fig. 1).

From (6)–(8) for the perfectly conducting surface case, a phase-curvature relationship [5] can be arrived at

$$\frac{K_u - K_v}{2k} = \pm \frac{1}{\cos 2\alpha} \tan \frac{\phi_{22} - \phi_{11}}{2} \quad (9)$$

A special case of (9) in which $\alpha = 0$ or $\pi/2$ occurs when the incident linear polarization coincides with one of the principal directions at the specular point, implying that there is no depolarization of the energy in the backscattered direction, in which case (9) is reduced to (1).

The results here are intended to apply to smooth convex perfect conductors at high frequencies in view of the re-

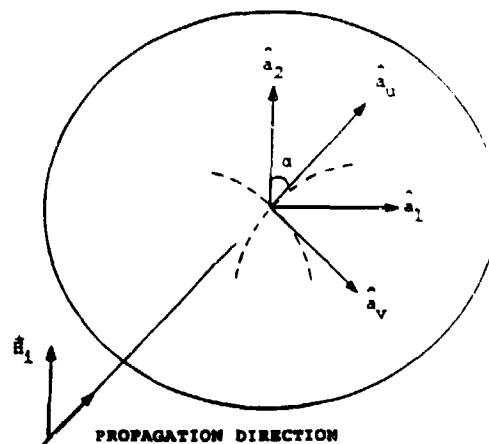


Fig. 1. Specular point coordinate system with dotted lines of principal curvatures and \hat{a}_1 , \hat{a}_2 as transmitting or receiving basis vectors.

strictions imposed by Bennett *et al.* [6] in deriving the correction field to the physical optics field. Yet to simplify the complicated case of surface backscattering of terrain, (1) is proposed to give a crude first-order model for such a case at look angles close to nadir for which multiple reflections and multipath effects may be neglected. Although the theory was developed for monostatic backscattering, (5)–(8) have recently been extended to the bistatic case [7], and (9) is found to take a similar form for the bistatic case. In order to check (9), it is useful here to recall the Sinclair (2×2) scattering matrices for linear (HV) polarization basis of the conducting flat plate (sphere) $[S]_s$, the $\lambda/4$ dielectric coated conducting wall $[S]_{\lambda/4}$, and the dihedral corner reflector $[S]_c$, where

$$[S(HV)]_s = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

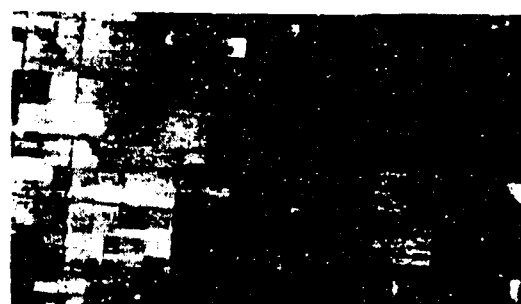
$$[S(HV)]_{\lambda/4} = \begin{bmatrix} 1 & 0 \\ 0 & \pm j \end{bmatrix}$$

$$[S(HV)]_c = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

yielding the relative co-polarization phases $(\phi_{HH} - \phi_{VV})_s = 0$, $(\phi_{HH} - \phi_{VV})_{\lambda/4} = \pm 90^\circ$, and $(\phi_{HH} - \phi_{VV})_c = \pm 180^\circ$, which satisfy the above equation. More detailed examples on displaying polarimetric target signatures are provided in [8].

III. RELEVANT RESULTS OF VECTOR RADIATIVE TRANSFER AND ROUGH SURFACE SCATTERING MODELS

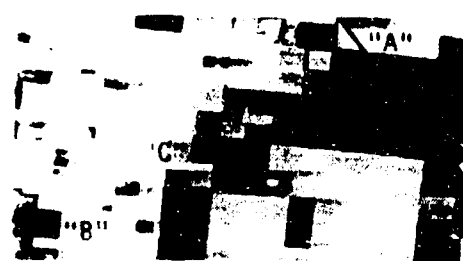
Radar returns from vegetative terrain are composed of contributions from the vegetation canopy and the underlying rough ground. The return from the vegetation canopy can be attributed to incoherent multiple scattering within a vegetation layer which consists of stalks, trunks, stems, foliage, etc. The volume fraction of vegetation components in a layer at L-band wavelengths is usually less than 1 percent, thus permitting us to model the vegetation scattering process by using the radiative transfer



• HH AMPLITUDE



• HH/VV PHASE DIFFERENCE - COLOR
• HH AMPLITUDE - BRIGHTNESS



• HH AMPLITUDE - RED
• VV AMPLITUDE - GREEN
• HV AMPLITUDE - BLUE

THE ADDITION OF PHASE
INFORMATION ENHANCES THE
DISCRIMINATION AND CLASSIFICATION
CAPABILITY OF RADAR SENSORS

Fig. 2. Polarization signature of aperture data (from [4]).

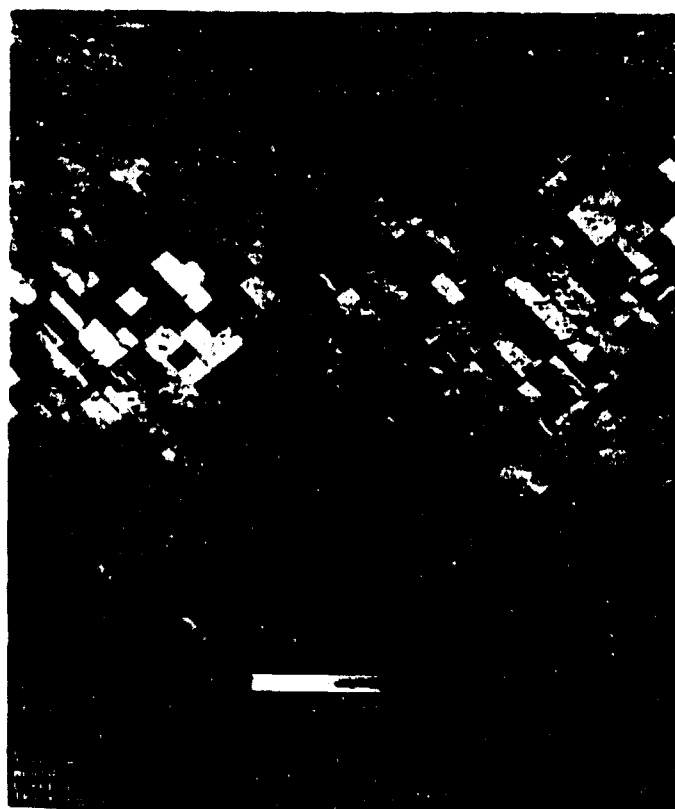


Fig. 3. Macomb, Illinois. SAR imaging (from [13]).

$$\text{Span } [S] = |S_{HH}|^2 + |S_{VV}|^2 + 2|S_{HV}|^2$$

approach which is valid for scattering in a very tenuous medium [9].

For the study of scatterometer backscatter from vegetated terrain, the radiative transfer model has been devel-

TABLE I
JPL CV-990 SYNTHETIC APERTURE RADAR (SAR)
(Also see Ulaby *et al.*, this issue, [13].)

| | |
|-------------------|--------------------|
| WAVELENGTH: | 24 cm |
| FREQUENCY: | 1225 MHz |
| POLARIZATIONS: | HH, VV, HV, VH |
| SWATH WIDTH: | 10 km - 20 km |
| SWATH LENGTH: | SEVERAL 100 km |
| RADAR RESOLUTION: | 10 meters (4-LOOK) |

oped [10], [11] and successfully used for the interpretation of radar backscattering strength versus angle of incidence, frequency, and polarization. Scatterometer and most terrain/sea imaging radars (SIR-A and -B) collect radar backscattering amplitudes averaged incoherently over many independent samples, thus destroying all relevant phase information. Hence, no simulation study of backscattered phase terms has been done yet due to the lack of reliable measurement data containing phase information.

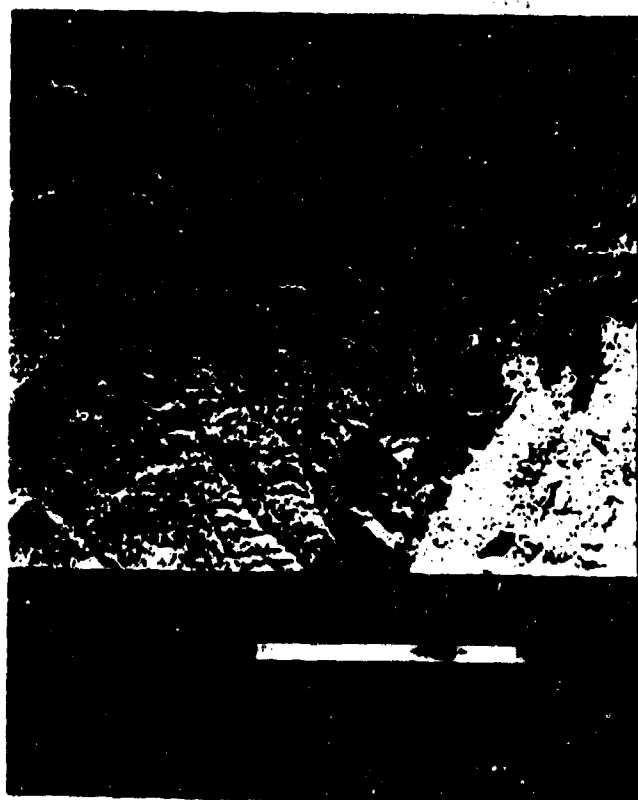
In order to theoretically investigate the phase behavior of VV and HH polarized radar backscatter from a vegetated canopy, we model a canopy as a scattering layer containing randomized Rayleigh spheres, based on the vector radiative transfer theory. It has been known that the phase difference between VV and HH polarized Rayleigh single scattering matrix elements are zero [12], which is consistent with the extended physical optics curvature theory introduced in Section II. In order to study the effect of multiple scattering from a layer embedded within random isotropic Rayleigh particles, we computed



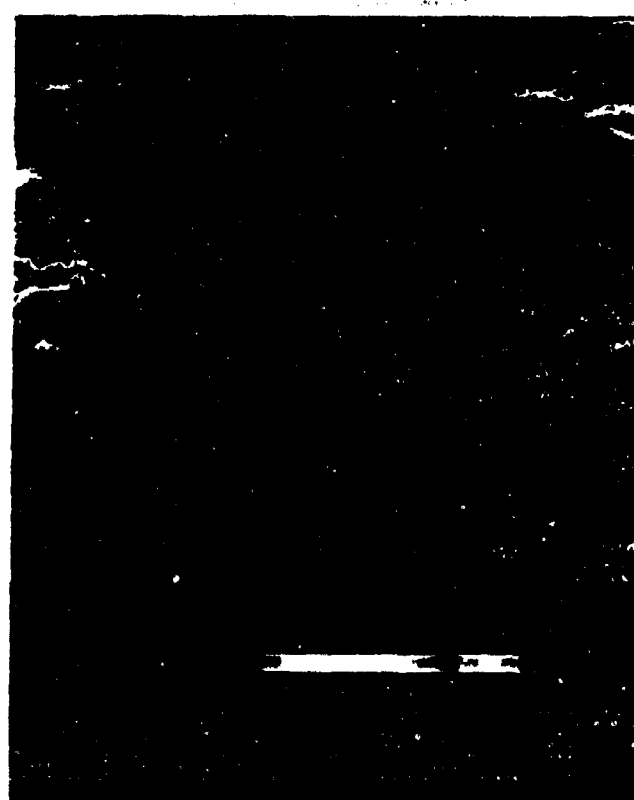
(a)



(b)



(c)



(d)

Fig. 4. Comparison of relative co-pol phase term for different types of terrain with/without vegetation canopy. (a) Macomb, Illinois. Little or no vegetation. Zero degree phase difference except in the town. (b) Mina, Nevada. Distinct phase difference. Signatures corresponding to agricultural region. (c) Winchester, Virginia. Phase "noise." Typical of multiple scattering in forested region. (d) Medicine Lake, California. A variety of surfaces including bare lava and forested regions.

phase difference between backscattered fields in VV and HH channels. The simulated result shows that the phase difference between VV and HH polarized signals at the considered wavelengths, is still inappreciable (for instance, less than 1° when layer albedo is 0.9, optical depth is 2.0). This means that the phase difference observed by JPL in vegetation mapping SAR imagery may be attributed to the fact of geometrical asymmetry due to preferred orientation of the terrain profile and of leaves, stems, and trunks. Further simulation studies using more refined vegetation scattering models of ellipsoids, prolate/oblate spheroids, discs, and needles are definitely necessary for correct interpretation of the observed anomalous phase difference phenomena.

IV. INTERPRETATION OF THE JPL POLARIMETRIC L-BAND (24 cm) CV-990 SAR SYSTEM

Polarimetric SAR images obtained with the JPL CV-990 SAR, as described in Table I, were made available [4], which included Fig. 2: polarization signature of aperture data; Fig. 3: Macomb, IL. SAR imaging

$$\text{Span } [S] = |S_{HH}|^2 + |S_{VV}|^2 + 2|S_{HV}|^2$$

and Fig. 4: comparison of relative co-pol phase term for different types of terrain with/without vegetation canopy.

From inspection of Figs. 2, 3 and 4(b), it is readily observed from comparison of the span versus the relative co-polarization phase terms that the latter contains very useful extra information clearly distinguishing electrically flat against rugged and volumetric scattering regions, as suggested by (1). Especially by comparison of Fig. 4(a) to (d), we observe that (1) separates electrically rough (Fig. 4(b)) from smooth (Fig. 4(a)) and mixed heterogeneously smooth/rough regions (Fig. 4(c)/(d)). It is also observed that with increasing look angle the relative co-polarization phase approaches 180° , which may be explained by the fact that volumetric multipath effects become dominant near the grazing angle. In addition, we observe that wherever the transmitted energy is scattered off backscattering direction or completely absorbed, no appreciable energy is received that is displayed as black regions, i.e., "RAM-painted black holes."

V. CONCLUSIONS AND RECOMMENDATIONS

Using the polarimetric L-band SAR data introduced, it was demonstrated that in addition to polarimetric amplitude also the polarimetric relative co-polarization phase term of the radar scattering matrix provides useful high-resolution image information. Based on our extended physical optics curvature relationship applicable to both the monostatic and bistatic cases, a first-order interpretation of the relative co-polarization phase images was suggested to differentiate between electrically smooth versus rugged or volumetric terrain targets (scatterer ensembles). In order to facilitate interpretation of the relative phase terms toward grazing at larger look angles, we recommend that our model be extended to incorporate the dielectric case.

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On the Polarimetric Contrast Optimization

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On the Polarimetric Contrast Optimization

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Abstract—The problem considered is one of finding the polarization state of an antenna such that a power ratio due to two different objects is

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optimized. It is reduced to an optimization problem of two Hermitian forms which can be simultaneously diagonalized using a well-known linear-algebraic construction. The corresponding polarization vectors are found. The calculations are performed directly on the expression for the energy density of the reflected wave as a function of the transmitter polarization and are, therefore, decoupled from the receiving antenna parameters. Such decoupling is particularly convenient in bistatic applications.

I. INTRODUCTION

There are numerous occasions in target-versus-clutter/clutter suppression applications where it is highly desirable to choose transmitting and receiving antenna parameters in such a way as to amplify a signal due to one object (target) while minimizing the signal due to the other (clutter). In this note, we consider the transmitting and receiving polarizations as such parameters and solve the corresponding optimization problem. It represents a natural extension of a three-stage procedure, developed in [1], to the two-target case.

Let us consider the reflection of a polarized radar signal by two targets (one of which is often distributed clutter) with known polarization characteristics.

To be more specific, let us choose a coordinate system with its center at the receiving antenna and with the z -axis along the direction from the receiving antenna to the target so that the reflected wave propagates in $-\hat{z}$ -direction. Furthermore, let us define a polarization state of a wave in

$$\vec{E} = |\vec{E}| (\cos \alpha \hat{x} + \sin \alpha e^{j\phi} \hat{y}) e^{j(\omega t \pm kz)} \quad (1)$$

as a two-dimensional complex column vector¹

$$\mathbf{E} = \begin{bmatrix} \cos \alpha \\ \sin \alpha e^{j\phi} \end{bmatrix} \quad (2)$$

where a boldface character indicates the polarization state. The entire (in general, bistatic) arrangement is illustrated in Fig. 1 which is similar to the situation and notation discussed in great detail in [1]. In accordance with [1], we will use subscripts T and R to indicate the transmitted and the reflected waves, respectively. The scattering matrix is then defined as [1]

$$\mathbf{E}_R = [\mathbf{S}] \mathbf{E}_T \quad (3)$$

and the voltage at the receiving antenna terminals [1], [2] is given by

$$V = \mathbf{h}^T \mathbf{E}_R = \mathbf{h}^T [\mathbf{S}] \mathbf{E}_T \quad (4)$$

Let us now consider the problem of optimizing the polarimetric contrast between two targets such as is encountered in target enhancement versus clutter suppression. We assume that the scattering matrices for the two objects (target and clutter) are known *a priori* (have been measured) and seek ways to use the information for optimal signal contrast. Note that a coherent clutter description is assumed via the scattering matrix, i.e., it is implied that the data are acquired on a time scale below the typical decorrelation time. The targets are then described by two known matrices $[\mathbf{A}]$ and $[\mathbf{B}]$, and a natural quantity to choose for optimization is

$$R = \frac{\mathbf{h}^T [\mathbf{A}] \mathbf{E}_T}{\mathbf{h}^T [\mathbf{B}] \mathbf{E}_T} \quad (5)$$

where $[\mathbf{A}] \mathbf{E}_T = \mathbf{E}_{RA}$ and $[\mathbf{B}] \mathbf{E}_T = \mathbf{E}_{RB}$, i.e., reflected wave

¹ It should be noted that, as indicated in Fig. 1 and discussed in [1], \mathbf{E}_T and \mathbf{E}_R are not coplanar in the general bistatic case and \mathbf{E}_T is defined in terms of the \hat{e}_1, \hat{e}_2 axes.

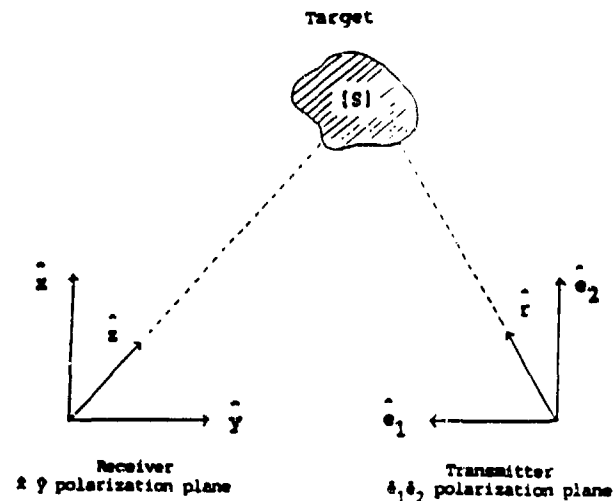


Fig. 1. General bistatic arrangement.

contributions due to targets A and B , respectively, and \mathbf{h} is the receiving antenna height, i.e., polarization state of a wave radiated by the receiving antenna in a given direction.

The optimization variables are \mathbf{h} and \mathbf{E}_T . The solution for the maximization of R in (5) is straightforward and is given by \mathbf{h} and \mathbf{E}_T such that

$$\mathbf{h}^T [\mathbf{B}] \mathbf{E}_T = 0 \quad (\text{provided } \mathbf{h}^T [\mathbf{A}] \mathbf{E}_T \neq 0). \quad (6)$$

There are, however, several reasons for a limited use of R -optimization in practice. First of all, if $[\mathbf{A}]$ and $[\mathbf{B}]$ are similar (have nearly equal matrix elements), the solution of (6) produces a very weak signal due to A . This fact may be especially important if the polarization purity of the antennas (\mathbf{h}) and (\mathbf{E}_T) is not very high. Secondly, the procedure does not apply when either \mathbf{h} or \mathbf{E}_T are fixed or the solution may not always exist in the $\mathbf{h} = \mathbf{E}_T$ backscattering case. Finally, and in our opinion, most importantly, the optimization based on (6) is essentially a mismatching procedure of the receiving antenna to the B -signal [1] and it tells one relatively little about the physics of the scattering process.

We, therefore, propose another ratio for optimization, in addition to (5), which "decouples" the scattering process from the receiving antenna state using the three-stage-procedure introduced in [1]. In order to produce stronger polarimetric contrast this procedure must be used in combination with (6).

II. PROBLEM FORMULATION

Consider the energy densities in the reflected wave due to the two targets as functions of the transmitted wave polarizations given by the following expressions [1]:

$$P_A = \mathbf{E}_{RA}^\dagger \mathbf{E}_{RA} = \mathbf{E}_T^\dagger [\mathbf{G}_A] \mathbf{E}_T \quad (7a)$$

$$P_B = \mathbf{E}_{RB}^\dagger \mathbf{E}_{RB} = \mathbf{E}_T^\dagger [\mathbf{G}_B] \mathbf{E}_T \quad (7b)$$

where the dagger denotes Hermitian conjugate $\mathbf{E}_{RA} = [\mathbf{A}] \mathbf{E}_T$, $\mathbf{E}_{RB} = [\mathbf{B}] \mathbf{E}_T$, $\mathbf{E}_R = \mathbf{E}_{RA} + \mathbf{E}_{RB}$, and $[\mathbf{G}_A] = [\mathbf{A}^\dagger][\mathbf{A}]$, $[\mathbf{G}_B] = [\mathbf{B}^\dagger][\mathbf{B}]$ are Hermitian Graves power matrices [3] for targets A and B , respectively. Clearly, (7a) and (7b) do not depend on the receiver polarization. The natural quantity to optimize is then

$$X = \frac{P_A}{P_B} = \frac{\mathbf{E}_T^\dagger [\mathbf{G}_A] \mathbf{E}_T}{\mathbf{E}_T^\dagger [\mathbf{G}_B] \mathbf{E}_T} \quad (8)$$

which is a ratio of two Hermitian forms and is to be optimized as a

function of E_T . It contains information about the scattering process itself (as far as contained in $[G_A]$ and $[G_B]$) and does not involve the receiving antenna polarization because it deals with the reflected energy density in free space. Furthermore, the information contained in solutions of (8) may give important clues to the inverse polarimetric problem of discerning a target structure from various reflected wave polarizations. Note, that once E_T is found such that X in (8) is optimized, one then proceeds to adjust h according to (6). The optimization of X in (8) depends on the positive-definiteness of the Hermitian form $E_T^\dagger [G_B] E_T$ as we will see in the next section. On the other hand, a necessary and sufficient condition for a Hermitian form to be positive definite is the positiveness of its eigenvalues.² In our case, however, the physics demands that eigenvalues be positive as they correspond to the reflected wave energy density values. We, therefore, conclude that both forms in (8) are positive-definite (nonnegative, strictly speaking), and we seek E_T such that X is extremal.

III. MATHEMATICAL SOLUTION

In this section, we will sketch a result well known in linear algebra [4]–[6] concerning simultaneous diagonalization of two Hermitian forms and then we will show how it is applied to the extremum search of X in [8].

Since both forms in (8) are Hermitian and nonnegative for any $[G_A]$, $[G_B]$ and E_T , we assume that the $[G_B]$ -form is positive definite³ (i.e., only $[G]$ with zero eigenvalues is excluded).

Let us, for simplicity, and for ease of comparison with the relevant mathematical literature, change notation and denote Hermitian forms corresponding to the two targets as follows:

$$a(x, x) = x^\dagger [G_A] x \quad (9a)$$

$$b(x, x) = x^\dagger [G_B] x \quad (9b)$$

where $x = E_T$ and the symbol " \dagger " stands for "defined as ...". We can then rewrite (8) as

$$X = \frac{a(x, x)}{b(x, x)} \quad (9c)$$

which is subject to optimization.

Following general prescriptions of the method of Lagrange multipliers, we form a quantity

$$a(x, x) - \lambda b(x, x) \quad (10a)$$

and then equate to zero its partial derivatives with respect to all the components of x , which results in the generalized characteristic equation

$$\det(a - \lambda b) = 0 \quad (10b)$$

where a and b are the matrices in (9).

The generalized eigenvectors corresponding to the roots of (10b) are given by

$$az_t = \lambda_t bz_t \quad (11)$$

and the z can be chosen so that [4]–[6]

$$b(z_i, z_j) = \delta_{ij}. \quad (12)$$

² This criterion follows easily from extremal properties of eigenvalues of a Hermitian form, i.e., the fact that for any $\|x\| = 1$, $\lambda_1 < (x^\dagger [H] x) < \lambda_n$, where λ_n is the largest eigenvalue and λ_1 is the smallest.

³ Actually, it is enough to assume that either the $[G_A]$ or $[G_B]$ -form is positive definite so that either X or X^{-1} must be optimized.

Let us now change variables according to

$$x_i = [O] x'_i \quad (13)$$

where $[O] = [z_1, z_2]$. Note that $[O]$ is not, in general, unitary because $(z'_i, z'_j) \neq \delta_{ij}$, but only $z'_i [b] z'_j = \delta_{ij}$.

As is shown in detail in [4], for instance, after the change of variables defined by (13), we obtain in the new variables

$$X = \frac{a(x, x)}{b(x, x)} = \frac{\lambda_1 |x'_1|^2 + \lambda_2 |x'_2|^2}{|x'_1|^2 + |x'_2|^2} \quad (14)$$

The entire procedure with (14) as a final result allows a clear geometric interpretation. Let the form $a(x, x)$ correspond to an ellipsoid not in a simple orthogonal space but in a generalized oblique space where an equation for a unit sphere is given by $b(z, z) = 1$, rather than $(z, z) = 1$. Then, in this generalized space a change of basis given by (13) "rotates" an ellipsoid of $a(x, x)$ to its principal axes.

It follows from (14) that $\lambda_1 < a(x, x)/b(x, x) < \lambda_2$, where λ_2 is the largest of the two eigenvalues.

In summary, the solution to the problem is given by λ_1 and λ_2 satisfying

$$\det(a - \lambda b) = 0 \quad (15a)$$

with corresponding z_1 and z_2 satisfying

$$az_t = \lambda_t bz_t \quad (15b)$$

which is a generalized eigenvalue problem. It is important to remember that (z_1, z_2) cannot be interpreted as a change-of-basis, because z_1 and z_2 as solutions of (15b) are not orthogonal, but only "b-orthogonal," i.e., $(z_i, bz_j) = \delta_{ij}$.

IV. DISCUSSION OF THE RESULTS

Now, referring to the radar-polarimetric notation used in Section I, let us summarize the results of Section III, where it has been shown that polarization states of the transmitting wave E_T which optimize the ratio $E_T^\dagger [G_A] E_T / E_T^\dagger [G_B] E_T$ are given by the generalized eigenvalue equation

$$[G_A] E_T = \lambda [G_B] E_T \quad (16a)$$

where the eigenvalues $\lambda_{1,2}$ are found from the quadratic expression

$$\det([G_A] - \lambda [G_B]) = 0. \quad (16b)$$

The quantity $0 \leq (\lambda_2 - \lambda_1)/(\lambda_1 + \lambda_2) \leq 1$ can be interpreted as a "measure of polarimetric contrast," because λ_1 and λ_2 are the minimum and maximum of the ratio X , respectively. Note that the procedure does not impose any constraints on the scattering matrices of the two objects because the Graves power matrices are Hermitian for any $[S]$ and the corresponding energy densities are always Hermitian forms. On the other hand, the necessity to measure the two scattering matrices separately is a very significant restriction from a practical point of view. However, in the "target in clutter" case the scattering matrix of the clutter can be measured with and without the target and if some information about the target $[S]$ is available it fits the present formalism. Consider a case where one of the matrices, e.g. $[G_B]$, is due to the clutter return and that one would like to set X in (8) to the maximum (as a function of E_T) in order to accomplish an effective target versus clutter discrimination. Then the solution is given by λ_2 , E_{T2} , which satisfy (16a) and (16b). As we pointed out in the introduction, one then uses the receiving antenna polarization to further improve clutter suppression. The easiest way to do this is, in

accordance with (6), to compute E_{RB} as

$$E_{RB} = [B]E_{T2} \quad (17)$$

and then to adjust the receiving antenna so that

$$V_B = h^T E_{RB} = 0. \quad (18)$$

To illustrate the procedure, let us briefly consider the example of an airborne manmade target of "certain reflection symmetry" in rain clutter. It is empirically well established [2] that when the raindrops are nearly spherical, the return wave is circularly polarized with the rotation sense opposite to the transmitted (also circularly polarized) wave. Thus, in the case of the transmitted circular polarization a complete polarization mismatch occurs between the antenna and the return signal, i.e., circularly polarized waves are required for efficient discrimination. An airborne target return, on the other hand, tends to cluster around linear polarizations (more or less so, for most aspects), but it is difficult to "pin it down" more precisely. Thus, one may want to try $[A] = [R]^{-1} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} [R]$ for the airborne target, where $[R]$ is a real rotation matrix which depends on the airborne target's position in the polarization plane (relative to \hat{H} -axis) and to try $[B] = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ for the rain. The circularly polarized wave $E_T = 1/\sqrt{2} \begin{bmatrix} 1 \\ j \end{bmatrix}$ will make V_B in (18) zero, but a small deviation of $[B]$ may significantly alter the result. On the other hand, such a choice of E_T may also cause very small returns due to $[A]$ depending on values of $[R]$.⁴ We, therefore, conclude that a solution based on (16a) and (16b) is needed together with (18). Note that this procedure is applied just as easily to nonspherical drops and fluctuating $[S]$ -elements as long as $[S]$ is known as a function of time. Indeed, since a measuring ability much below the decorrelation time has been assumed, $[S]$ can be measured and X can be optimized for each time segment separately. It is perhaps useful to give an estimate of the time scales required for the "fast" measurement in the case of rain clutter. Let us consider 3 GHz waves ($\lambda = 10$ cm) scattered by the rain of average strength with average drops size 0.5 mm. Typical decorrelation times [7], [8] are then on the order of 10–100 ms (for moderate rain rates). Thus, the complete scattering matrix measurement must be completed during the time < 1 ms which is well satisfied by several modern polarimetric radars [8]. Note, that by systematically varying E_T ("polarization state scanning") and finding maxima and minima of the response power, one can find λ_1 , λ_2 , and $k = (\lambda_2 - \lambda_1)/(\lambda_1 + \lambda_2)$ experimentally, even if $[A]$ and $[B]$ are not known. Such a procedure may be of importance in various problems of remote sensing when adaptive polarization state scanning is available.

V. SUMMARY

We have considered a problem of optimizing the "signal versus clutter"-like polarimetric ratio directly in terms of the energy density of the reflected wave due to the two separate parts of the signal. The theorem about simultaneous diagonalization of two Hermitian forms was used to solve the problem. The procedure decouples the receiving from the transmitting antenna similar to the method in [1], and it allows one to obtain more insight into the physics of the scattering process. Then the procedure is combined with variations of the receiving antenna polarization state to obtain a more efficient optimization algorithm. Our procedure complements several papers [9]–[12] devoted to the same topic in that it considers the problem in

the framework of a completely polarized formalism of polarization states, scattering matrices, and energy density forms. In physical terms, we solved (for the first time) the problem of the polarimetric contrast optimization in the fast measurement (much below the decorrelation time) regime.

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⁴ Even in the case of $[R] = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$, 50 percent of $P_A = V_A V_A^*$ is lost when E_T is chosen to be $1/\sqrt{2} \begin{bmatrix} 1 \\ j \end{bmatrix}$.

离散 Radon 变换

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摘 要

本文提出一种离散拉东变换。如同离散型傅里叶变换那样，它适用于电子计算机的使用。在本文中，首先给出它的定义，其次研究了这种离散拉东变换的一些性质：线性性质、线性变换性质、相似性质、位移性质、导数性质、关于傅里叶变换的性质以及卷积性质等，尤其是还研究了它的逆变换。

关键词：离散，Radon 变换，定义，性质。

一、引 言

1917年，拉东(Radon)研究某些几何问题时，提出了一种变换[1]，后人称之为拉东变换[2-5]。从六十年代中期起，在研究无线电天文学[6]、结构生物学[7]、X射线摄影[8][9]、地球物理[10][11]以及电磁逆散射[12]等不同的领域中，人们逐渐使用拉东变换，因而这种变换的重要性愈加明显。尤其是需要指出的，对于研究电磁成像理论或者电磁逆散射问题来说，拉东变换成为不可缺少的工具。例如，如果我们从接收信号中，获得有关物体(或者目标)的横截面积的信息，那么从横截面积来重构目标形状时，通常要利用拉东变换。

在应用拉东变换来重构目标形状时，需要借助于电子计算机来完成。但已发现，现有的拉东变换，如同连续型傅里叶变换那样，不便于电子计算机的数值计算。因此，急需进一步解决这个问题。

本文提出一种离散拉东变换。如同离散型傅里叶变换那样，它适用于电子计算机的使用。在本文中，首先给出它的定义，其次研究了这种离散拉东变换的一些性质：线性性质、线性变换性质、相似性质、位移性质、导数性质、关于傅里叶变换的性质以及卷积性质等，尤其是还研究了它的逆变换。

本文收到日期：1988年12月25日

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二、离散拉东变换的定义及其基本性质

1 定义

在欧氏空间上函数 f 的拉东变换为

$$Rf(\xi) = \hat{f}(\xi, p) = \int f(x) \delta(p - \xi \cdot x) dx \quad (1)$$

式中 x 是 R^n 中的矢量, $x = (x_1, x_2, \dots, x_n)$, $dx = dx_1 dx_2 \dots dx_n$, $\delta(\cdot)$ 是 Dirac Delta 函数, ξ 是 R^n 中的单位矢量以及超平面由下式给定

$$p = \xi \cdot x = \xi_1 x_1 + \xi_2 x_2 + \dots + \xi_n x_n \quad (2)$$

现在假设 $f(x)$ 的采样函数为

$$f_s(x) = \frac{1}{M} \sum_m f(x_m) \delta(x - x_m) \quad (3)$$

式中 M 为常数, 通常取 $M=1$, 以及 x_m 是 R^n 中的矢量, 它们由采样定理来确定, 那么我们称

$$\hat{f}(\xi, p) = \frac{1}{M} \sum_m f(x_m) \delta(p - \xi \cdot x_m) \quad (4)$$

为 $f(x)$ 的离散拉东变换。记作 $Rf(x_m)$, 即

$$Rf(x_m) = \hat{f}(\xi, p)$$

事实上, 将式(3)代入式(1)便得到式(4)

2 对称性

$$\hat{f}(-\xi, -p) = \hat{f}(\xi, p) \quad (5)$$

3 线性性质

$$R\{c_1 f(x_m) + c_2 g(x_m)\} = c_1 Rf(x_m) + c_2 Rg(x_m) \quad (6)$$

4 线性变换性质

若 A 和 B 是两个非奇异矩阵, 且

$$\xi = B\xi', \eta = A\xi, \eta_m = Ax_m, B^T = A^{-1} \quad (7)$$

式中 B^T 表示 B 的转置, A^{-1} 为 A 的逆矩阵, 那么

$$Rf(A^{-1}\eta_m) = |A| Rf(x_m) \quad (8)$$

特例: 若

$$A^{-1} = \lambda I \quad (9)$$

式中 I 为单位矩阵, 则

$$Rf(\lambda\eta_m) = \frac{1}{|\lambda|} \hat{f}\left(\frac{\xi}{\lambda}, p\right) \quad (10)$$

5 相似性质

对于任意的非零实数 λ , 我们有

$$\hat{f}(\lambda\xi, \lambda p) = \frac{1}{|\lambda|} \hat{f}\left(\frac{\xi}{\lambda}, p\right) \quad (11)$$

6 位移性质

$$Rf(\bar{x}_m - \bar{a}) = \hat{f}(\xi, p - \xi \cdot \bar{a}) \quad (12)$$

式中 \bar{a} 为常矢。

三、 \hat{f} 的傅里叶变换1 \hat{f} 关于 p 的傅里叶变换

$$F(\rho\xi) = \mathcal{F}\{\hat{f}(\xi, p)\} = \frac{1}{M} \sum_m f(\bar{x}_m) e^{-j2\pi\rho\xi \cdot \bar{x}_m} \quad (13)$$

特例: 令 $\rho=0$, 得

$$\int_{-\infty}^{\infty} \hat{f}(\xi, p) dp = \frac{1}{M} \sum_m f(\bar{x}_m) \quad (14)$$

2 逆变换

对于任何矢量 $\bar{x}_n, \bar{x}_m \in \{\bar{x}_m\}$, 且当 $m \neq n$ 时有 $\xi \cdot \bar{x}_m \neq \xi \cdot \bar{x}_n$, 于是

$$\hat{f}(\bar{x}_n) = M \hat{f}(\xi, \xi \cdot \bar{x}_n) \quad (15)$$

2 \hat{f} 关于 p 的傅里叶变换

$$\mathcal{F}\{\hat{f}(\xi, p)g(\xi, p)\} = \frac{1}{M^2} \sum_m f(\bar{x}_m)g(\bar{x}_m) e^{-j2\pi\rho\xi \cdot \bar{x}_m} \quad (16)$$

特例: 令 $\rho=0$, 得

$$\int_{-\infty}^{\infty} \hat{f}(\xi, p)g(\xi, p) dp = \frac{1}{M^2} \sum_m f(\bar{x}_m)g(\bar{x}_m) \quad (17)$$

如果 $f=g, \hat{f}=g$, 那末式(17)变成

$$\int_{-\infty}^{\infty} [\hat{f}(\xi, p)]^2 dp = \frac{1}{M^2} \sum_m [f(\bar{x}_m)]^2 \quad (18)$$

这时, 可将式(18)称为此变换的 Parseval 公式。

四、变换的导数

1 \hat{f} 关于 p 的导数

$$\frac{\partial \hat{f}}{\partial p} = \frac{1}{M} \sum_m f(\bar{x}_m) \frac{\partial}{\partial p} \delta(p - \xi \cdot \bar{x}_m) \quad (19)$$

$$\frac{\partial^2 \hat{f}}{\partial p^2} = \frac{1}{M} \sum_m f(\bar{x}_m) \frac{\partial^2}{\partial p^2} \delta(p - \xi \cdot \bar{x}_m) \quad (20)$$

2. 关于 ξ_k 的导数

$$\begin{aligned}\frac{\partial f}{\partial \xi_k} &= \frac{1}{M} \sum_m f(\bar{x}_m) \frac{\partial}{\partial \xi_k} \delta(p - \frac{1}{M} \bar{x}_m) \\ &= -\frac{1}{M} \frac{\partial}{\partial p} \sum_m x_{mk} f(\bar{x}_m) \delta(p - \frac{1}{M} \bar{x}_m)\end{aligned}\quad (21)$$

式中 ξ_k 和 x_{mk} 分别为 ξ 和 \bar{x}_m 的第 k 个分量, 即有

$$\frac{\partial}{\partial \xi_k} Rf(\bar{x}_m) = -\frac{\partial}{\partial p} R\{x_{mk} f(\bar{x}_m)\} \quad (22)$$

类似地, 可得

$$\frac{\partial^2}{\partial \xi_k^2} Rf(\bar{x}_m) = \frac{\partial^2}{\partial p^2} R\{x_{mk}^2 f(\bar{x}_m)\} \quad (23)$$

$$\frac{\partial^2}{\partial \xi_r \partial \xi_s} Rf(\bar{x}_m) = \frac{\partial^2}{\partial p^2} \{x_{mr} x_{ms} f(\bar{x}_m)\} \quad (24)$$

式中 ξ_r 和 ξ_s 分别为 ξ 的第 r 个和第 s 个分量。

3. $\frac{\partial^k f}{\partial p^k}$ 的傅里叶变换

$$\text{假设 } \lim_{|p| \rightarrow \infty} \frac{\partial^r f}{\partial p^r} = 0, \quad r = 0, 1, 2, \dots, k-1 \quad (25)$$

那末

$$\mathcal{F}\left\{\frac{\partial^k f}{\partial p^k}\right\} = (j2\pi\rho)^k F(\rho\xi) \quad (26)$$

4. $\frac{\partial f}{\partial \xi_k}$ 的傅里叶变换

$$\mathcal{F}\left\{\frac{\partial f}{\partial \xi_k}\right\} = -j \frac{2\pi\rho}{M} \sum_m x_{mk} f(\bar{x}_m) e^{-j2\pi\rho \bar{x}_m} \quad (27)$$

$$\mathcal{F}\left\{\frac{\partial^2 f}{\partial \xi_k^2}\right\} = \left(\frac{j2\pi\rho}{M}\right)^2 \sum_m x_{mk}^2 f(\bar{x}_m) e^{-j2\pi\rho \bar{x}_m} \quad (28)$$

$$\mathcal{F}\left\{\frac{\partial^2 f}{\partial \xi_r \partial \xi_s}\right\} = \left(\frac{j2\pi\rho}{M}\right)^2 \sum_m x_{mr} x_{ms} f(\bar{x}_m) e^{-j2\pi\rho \bar{x}_m} \quad (29)$$

五、卷 积

1. 卷积的变换

$$\text{若 } f_1(\bar{x}) = \frac{1}{M^2} \sum_m g(\bar{x}_m) \sum_i h(\bar{x}_i - \bar{x}_m) \delta(\bar{x} - \bar{x}_i) \quad (30)$$

则

$$f_1(\xi, p) = \frac{1}{M^2} \sum_m g(\bar{x}_m) \sum_i h(\bar{x}_i - \bar{x}_m) \delta(p - \frac{1}{M} \bar{x}_i) \quad (31)$$

显然, $f_c(\xi, p)$ 关于 p 的傅里叶变换为

$$\mathcal{F}\{f_c(\xi, p)\} = \frac{1}{M^2} \sum_m g(\bar{x}_m) \sum_i h(\bar{x}_i - \bar{x}_m) e^{-i2\pi p \bar{x}_i \cdot \bar{x}_i}, \quad (32)$$

特例: 令 $p=0$, 得

$$\int_{-\infty}^{\infty} f_c(\xi, p) dp = \frac{1}{M^2} \sum_m g(\bar{x}_m) \sum_i h(\bar{x}_i - \bar{x}_m) \quad (33)$$

2 $g(\xi, \bar{p})$ 与 $h(\xi, \bar{p})$ 的卷积

$g(\xi, p)$ 与 $h(\xi, \bar{p})$ 卷积为

$$f_{gh}(\xi, p) = \frac{1}{M^2} \sum_m g(\bar{x}_m) \sum_i h(\bar{x}_i) \delta(p - \xi \cdot \bar{x}_m - \xi \cdot \bar{x}_i) \quad (34)$$

它的傅里叶变换为

$$\begin{aligned} \mathcal{F}\{f_{gh}(\xi, p)\} &= \mathcal{F}\{g(\xi, p)\} \mathcal{F}\{h(\xi, \bar{p})\} \\ &= \frac{1}{M^2} \sum_m g(\bar{x}_m) \sum_i h(\bar{x}_i) e^{-i2\pi p(\bar{x}_i \cdot \bar{x}_m + \bar{x}_i \cdot \bar{x}_i)} \end{aligned} \quad (35)$$

特例: 令 $p=0$, 得

$$\int_{-\infty}^{\infty} f_{gh}(\xi, p) dp = \frac{1}{M^2} \sum_m g(\bar{x}_m) \sum_i h(\bar{x}_i) \quad (36)$$

六、逆变换

下面推导逆变换的积分表示式, 并且进一步讨论维数 n 分别为奇数和偶数的两种情形。

1 一般公式

由式(13)可推出

$$f(\bar{x}_m) = \int_{|\xi|=1} G(\xi, \xi \cdot \bar{x}_m) d\xi \quad (37)$$

式中

$$G(\xi, t) = \int_0^{\infty} MF(\rho\xi) e^{i2\pi\rho t} \rho^{n-1} d\rho \quad (38)$$

因为式(37)是沿单位球面 $|\xi|=1$ 的积分, 所以式(38)可分成两部分, 即

$$\begin{aligned} G(\xi, t) &= \frac{M}{2} \int_0^{\infty} F(\rho\xi) e^{i2\pi\rho t} \rho^{n-1} d\rho \\ &\quad + \frac{M}{2} \int_0^{\infty} F(-\rho\xi) e^{-i2\pi\rho t} \rho^{n-1} d\rho \end{aligned} \quad (39)$$

于是, 利用 f 的导数之傅里叶变换以及 f 的对称性, 可求出

$$\begin{aligned} G(\xi, t) &= \frac{M}{2(j\pi)^{n-1}} \left\{ \int_0^{\infty} \int_{-\infty}^{\infty} D_{n-1}(\xi, p) e^{-j2\pi p(p-1)} dp d\rho \right. \\ &\quad \left. + (-1)^{n-1} \int_0^{\infty} \int_{-\infty}^{\infty} D_{n-1}(\xi, p) e^{-j2\pi p(p-1)} dp d\rho \right\} \end{aligned} \quad (40)$$

式中

$$D_{n-1}(\xi, t) = \frac{\partial^{n-1} f(\xi, t)}{\partial t^{n-1}} \quad (41)$$

2 n 为奇数

当 n 为奇数, 式(40)变成

$$G(\xi, t) = \frac{M}{2(j2\pi)^{n-1}} \frac{\partial^{n-1} f(\xi, t)}{\partial t^{n-1}} \quad (42)$$

故

$$f(x_m) = \frac{M}{2(j2\pi)^{n-1}} \int_{|\xi|=1} D_{n-1}(\xi, t) \Big|_{t=\xi \cdot x_m} d\xi \quad (43)$$

3 n 为偶数

当 n 为偶数, 式(40)变成

$$\begin{aligned} G(\xi, t) &= \frac{iM}{2(j2\pi)^{n-1}} \int_{-\infty}^{\infty} \frac{D_{n-1}(\xi, t)}{\pi(p-i)} dp \\ &= \frac{iM}{2(j2\pi)^{n-1}} H\{D_{n-1}(\xi, t)\} \end{aligned} \quad (44)$$

式中 $H\{\cdot\}$ 表示 Hilbert 变换。因此

$$f(x_m) = \frac{iM}{2(j2\pi)^{n-1}} \int_{|\xi|=1} H_{n-1}(\xi, t) \Big|_{t=\xi \cdot x_m} d\xi \quad (45)$$

式中

$$H_{n-1}(\xi, t) = H\left\{\frac{\partial^{n-1} f(\xi, t)}{\partial t^{n-1}}\right\} \quad (46)$$

七、结 束 语

1985年5月至1986年5月本赴英访问考察。其中在11月, 应伊利诺斯大学芝加哥分校电气工程系通讯实验室主任 Boerner 教授的邀请, 进行有关逆散射问题的合作研究。本文便是逆散射项目的研究成果之一。

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On the Discrete Radon Transform

Lin Shiming (S. M. Lin) W.-M. Eoerner

In a wide variety of profile reconstruction technique a need often arises to deduce the three-,two-or one-dimensional distribution of physical quantities from their projections, e. g., in radio-astronomy, in structural biology, in x-ray photography, in geophysics and in electromagnetic inverse scattering, etc. The underlying theory was first developed and formulated by Radon in 1917 and the basic formula is known as the Radon transform.

In order to use the Radon transform conveniently in computer numerical applications, a discrete Radon transform is first defined in this paper. The results presented in this paper are believed to be new, as they have not been previously reported in open literature.

Several important properties of this discrete transform are studied such as the symmetry, linearity, linear transformation, derivatives, convolution and inversion of this transform. It is shown that the properties of this transform are analogous to the ordinary Radon transform. Obviously, this discrete transform can be used conveniently for discrete distribution.

Key words: Discrete, Radon transform, definition, properties.

Optimal reception of partially polarized waves

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Various aspects of the physics of partially polarized waves are discussed with applications to optical (lidar) reception problems. We focus on the issue of the optimal intensity reception of partially polarized waves scattered off a fluctuating object (ensemble of scatterers) of known polarization properties (measured Mueller matrix). Expressions for total available intensity and adjustable (polarization-dependent) intensity are derived in a clear and novel manner by using the coherency matrix approach. A general numerical technique is developed and illustrated for the optimization of adjustable intensity as a function of transmitted polarization. Closed-form expressions are derived for two important subcases, and numerical illustrations for the general case are discussed in detail, including the use of relevant experimental data.

1. INTRODUCTION

When a time-dependent scatterer is illuminated by a monochromatic (completely polarized) wave, it reflects a wave whose amplitude and phase are functions of time. The scattered wave is nonmonochromatic and therefore partially polarized.¹⁻³ Properties of such waves are well understood,²⁻⁷ and the appropriate mathematical formalism based on the coherency matrix^{2,3} and the Mueller matrix^{4,7} has been used extensively. Furthermore, there has been a renewed interest in the relation between Mueller and Jones methods of treating polarized light.⁸⁻¹⁰ In this paper we are concerned with the general case of partially polarized light, and the Mueller matrix apparatus is employed throughout. Below, we briefly review the underlying physics because it is sometimes lost in formal applications of the Mueller and coherency matrix techniques. The concepts of total and adjustable intensity are then defined, and the optimization problem is outlined. In Section 2 we derive expressions for the total intensity and the adjustable intensity that is due to the incoming partially polarized wave. In Section 3 we formulate and solve the corresponding mathematical problem of adjustable-intensity optimization as a function of the transmitted Stokes vector (for a given Mueller matrix representing an ensemble of fluctuating particles). Detailed numerical examples are given in Section 4.

Consider a quasi-monochromatic wave at a fixed point in space whose temporal behavior is described by the Jones vector

$$\mathbf{E} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} |E_x| \exp(i\delta_x) \\ |E_y| \exp(i\delta_y) \end{bmatrix} = \{A(t)\hat{x} + B(t)\exp[i\phi(t)]\hat{y}\} \exp(i\omega t), \quad (1)$$

where the time dependence of $A(t)$, $B(t)$, and $\phi(t)$ causes a spectral spread Δf such that $\Delta f \ll \omega/(2\pi)$. Imagine an ellipsometer at a fixed point in space that is capable of measuring the signal that is due to Eq. (1). If the measurement duration τ satisfies $\tau \ll (2\pi)/\Delta f$, then the wave described by Eq. (1) can be considered completely polarized. In this paper, we will be concerned with the case $\tau \gg (2\pi)/\Delta f$ (i.e., long

averaging times) when the wave is partially polarized. In order to characterize partial polarization quantitatively, we define the polarization coherency matrix² of a partially polarized wave as

$$[J] = \begin{bmatrix} \langle E_x^* E_x \rangle & \langle E_x^* E_y \rangle \\ \langle E_y E_x^* \rangle & \langle E_y E_y^* \rangle \end{bmatrix}, \quad (2)$$

where

$$\langle \dots \rangle = \lim_{T \rightarrow \infty} \left[\frac{1}{2T} \int_{-T}^{+T} (\dots) dt \right].$$

In the case of quasi-monochromatic waves, the rapid $\exp(i\omega t)$ oscillations will be averaged out, and only the smooth envelopelike variations will contribute to the field correlations and therefore to the elements of $[J]$. Furthermore, the elements of $[J]$ can be written as a sum of two components, one of which corresponds to a completely polarized wave (with time-independent phase relations in Eq. (1)) and the other of which describes the unpolarized part (a set of all polarization states distributed with equal probability during the measurement time τ).^{2,3} The relative weight of the polarized part is given by the degree of polarization p defined as

$$p = \left[1 - \frac{4(\det[J])}{(J_{xx} + J_{yy})^2} \right]^{1/2}. \quad (3)$$

The question then arises as to how should one tune the receiver's state of polarization in order to obtain an optimal response (e.g., a maximum of absorbed intensity). The answer depends on J and p , both of which, in turn, depend on the transmitted-wave polarization and the scatterer properties. Defining a real (4×1) Stokes vector S in terms of $[J]$ as²⁻⁴

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} J_{xx} + J_{yy} \\ J_{xx} - J_{yy} \\ J_{xy} + J_{yx} \\ -i(J_{xy} - J_{yx}) \end{bmatrix} \quad (4)$$

enables us to write p as

$$p = \frac{(S_1^2 + S_2^2 + S_3^2)^{1/2}}{S_0}. \quad (5)$$

Let us denote by T and R the Stokes vectors of the transmitted and reflected waves, respectively; then the depolarization properties of a linear passive medium (say, a collection of small fluctuating particles) is described by a (4×4) real matrix $[M]$,^{4,11} called the Mueller matrix, according to¹²

$$R = [M]T. \quad (6)$$

Here, T satisfies

$$T_0 = (T_1^2 + T_2^2 + T_3^2)^{1/2}$$

because the transmitted wave is assumed to be completely polarized ($p = 1$).

To summarize, a monochromatic wave of given polarization is transmitted and scattered off an ensemble of fluctuating objects, resulting in a scattered wave's being partially polarized (on the scale of the receiver measurement time τ). The scattered wave is described by the real (4×1) Stokes vector R , and the scatterer is described by the real (4×4) Mueller matrix $[M]$. It is our goal to find transmitted polarizations for which the received signal is maximal for a given (measured) $[M]$. As already mentioned, the scattered wave can be decomposed into completely polarized and unpolarized parts.² Only the former can be fully absorbed by the receiver. The weighting factor (degree of polarization) depends on both T and $[M]$, and it determines the efficiency of reception.

2. DERIVATION OF THE EXPRESSIONS FOR THE TOTAL AND ADJUSTABLE INTENSITIES

In order to find an expression for the energy absorbed by the polarimeter as compared with the intensity contained in the scattered wave given by R_0 , we first notice that the completely polarized part of the energy can be totally absorbed by the receiver with a properly chosen polarization.^{4,13} To be more specific, let

$$R = P + U, \quad (7a)$$

where the polarized P and unpolarized U parts are uniquely determined^{2,4} by the relations

$$P = \begin{bmatrix} (R_1^2 + R_2^2 + R_3^2)^{1/2} \\ R_1 \\ R_2 \\ R_3 \end{bmatrix}, \quad U = \begin{bmatrix} R_0 - (R_1^2 + R_2^2 + R_3^2)^{1/2} \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (7b)$$

The degree of polarization of R is given by

$$p = (R_1^2 + R_2^2 + R_3^2)^{1/2}/R_0.$$

The completely polarized component of R can be written in spherical coordinates of the Stokes subspace as^{4,14}

$$\theta = \tan^{-1}(R_3/R_1), \quad -\pi/2 \leq \theta \leq \pi/2, \quad (8a)$$

$$\epsilon = \sin^{-1}(R_2/(R_1^2 + R_3^2)^{1/2}), \quad -\pi/4 \leq \epsilon \leq \pi/4, \quad (8b)$$

where θ and ϵ are the tilt and ellipticity angles, respectively, and are further related to the Jones-vector parameters E_1 , E_2 , δ_1 , and δ_2 (Refs. 2 and 4) by

$$\chi = \frac{E_2}{E_1} = \frac{|E_2|}{|E_1|} \exp(i\delta_2 - \delta_1) = \frac{\tan \theta + i \tan \epsilon}{1 - i \tan \theta \tan \epsilon}, \quad (9)$$

where χ is the complex polarization ratio.

Equations (8) and (9) allow us to reconstruct the polarization ellipse (Jones vector) of the polarized component in terms of R .

Denote the Jones vector of the completely polarized component as E_s , where the subscript s stands for the scattered wave. If h is defined as the polarization state of the wave radiated by the receiver (when used as a transmitter),¹⁵ then the receiver must be adjusted according to

$$h = E_s^* \quad (10)$$

to absorb all the energy contained in the polarized component.

Consider now the energy absorbed by the receiver that is due to the unpolarized component of the scattered wave, i.e., the part described by U . Let us further suppose that the receiver is in the complete (but otherwise arbitrary) polarization state characterized by the Jones vector h or equivalently by the Stokes vector H .

The key step here is to realize that an unpolarized wave can always be represented by an incoherent sum of any two orthogonal completely polarized waves of equal intensity.² Let us represent the received wave as $1/2(H + H_\perp)$ where H_\perp is the Stokes vector orthogonal to H . The H part will be absorbed by the receiver, and the H_\perp part will be totally rejected, leading to a 50% efficiency for the reception of the unpolarized waves. To illustrate this point, consider the following representation for R :

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 \\ 0 \\ 0 \\ +1 \end{bmatrix}_{\text{LHC}} + \frac{1}{2} \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}_{\text{RHC}},$$

which is an equal mixture of left-hand-circular (LHC)-polarized waves and right-hand-circular (RHC)-polarized waves. If the receiver is RHC tuned, it will receive 1/2 of the total energy. This argument applies for any h and H pair, and we therefore conclude that the total available energy consists of two parts: 100% reception efficiency for P and 50% reception efficiency for U . The former can be affected by changing the polarization state of the receiver, whereas the latter is polarization independent.

In order to obtain a simple expression for the total available intensity, we rewrite R as

$$R = P + U = \begin{bmatrix} pR_0 \\ R_1 \\ R_2 \\ R_3 \end{bmatrix} + \begin{bmatrix} (1-p)R_0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (11)$$

where $p = (R_1^2 + R_2^2 + R_3^2)^{1/2}/R_0$. Since the energy density is given by the first element R_0 of the Stokes vector R , we can write the following expression for the total available intensity (normalized):

$$P = pR_0 + 1/2(1-p)R_0 = 1/2R_0(1+p) \\ = 1/2R_0 \left[1 + \frac{(R_1^2 + R_2^2 + R_3^2)^{1/2}}{R_0} \right], \quad (12)$$

where the first term represents adjustable intensity and the second term corresponds to noiselike intensity with 50% reception efficiency. A similar expression was obtained in Ref. 15 by an entirely different and somewhat less transparent method.

Let us briefly summarize the derivation of Eq. (12). First, we decompose the scattered partially polarized wave into its completely polarized and unpolarized components and note that by properly adjusting the receiver we can collect all the energy contained in the polarized part. Next, we decompose the unpolarized part into an equal sum of incoherent orthogonally polarized waves and notice that any one of them can be absorbed, resulting in 50% reception efficiency.

3. ADJUSTABLE-INTENSITY OPTIMIZATION

As we have seen above, the pR_0 part of Eq. (12) represents adjustable intensity because it depends strongly on the receiver polarization state, and it can vary anywhere within the $(0, pR_0)$ interval. On the other hand, the $1/2(1-p)R_0$ part of Eq. (12) is noiselike because it is completely independent of the receiver polarization and therefore cannot be controlled. Note that both terms depend on p , which in turn depends on the transmitted polarization T and on the fluctuating scatterer $[M]$ by means of Eqs. (5) and (6). In most optimization situations, we would like to minimize the noiselike part so that as much energy as possible is kept under control. The remaining part can then be matched or mismatched, depending on the particular application. The ratio of the two terms in Eq. (12) is $2p/(1-p)$ and increases with p ; therefore optimization of $p = p(T, [M])$ is often important. On the other hand, intensity optimization is a compromise of minimizing the noiselike part (by maximizing p) while keeping the overall intensity sufficiently high.

Optimizing the adjustable (i.e., polarization-dependent) part $pR_0 = (R_1^2 + R_2^2 + R_3^2)^{1/2}$ of Eq. (12) requires that $\|R\| = (R_1^2 + R_2^2 + R_3^2)^{1/2}$ be optimized (maximized or minimized) as a function of T for a given $[M]$. In order to optimize the adjustable-intensity term pR_0 , we rewrite Eq. (6) in the more-convenient form:

$$\begin{bmatrix} R_0 \\ R \end{bmatrix} = \begin{bmatrix} M_{00} & \tilde{a}^T \\ \tilde{m} & [\tilde{M}] \end{bmatrix} \begin{bmatrix} T_0 \\ T \end{bmatrix}, \quad (13a)$$

where $(\tilde{\cdot})$ indicates three-dimensional Stokes subspaces and \tilde{a} , \tilde{m} , and $[\tilde{M}]$ are taken from $[M]$:

$$\tilde{a} = \begin{bmatrix} M_{01} \\ \vdots \\ M_{03} \end{bmatrix}, \quad \tilde{m} = \begin{bmatrix} M_{10} \\ \vdots \\ M_{30} \end{bmatrix}, \quad [\tilde{M}] = \begin{bmatrix} M_{11} & \dots & M_{13} \\ \vdots & & \vdots \\ M_{31} & \dots & M_{33} \end{bmatrix}. \quad (13b)$$

Let us now focus on optimizing $\|R\| = (R_1^2 + R_2^2 + R_3^2)^{1/2} = pR_0$ for some completely polarized T such that $T^T = T = 1$. To this end, Eq. (13a) is reduced to

$$R_0 = M_{00} + (\tilde{a}^T, T), \quad (14a)$$

$$\tilde{R} = \tilde{m} + [\tilde{M}]T, \quad (14b)$$

A. Some Closed-Form Solutions

Two special cases of Eq. (14b) are now considered, which show that the general solution for T is a compromise between the optimization of a quadratic form involving $[\tilde{M}]$ and the influence of the inhomogeneous term \tilde{m} .

(1) Consider the case $\|\tilde{m}\| \ll \|[\tilde{M}]T\|$ such that

$$\tilde{R} \simeq [\tilde{M}]T, \quad T^T = 1; \quad (15a)$$

then

$$\|\tilde{R}\|^2 = (\tilde{R}^T, \tilde{R}) = (T^T, [\tilde{G}]T), \quad (15b)$$

where $[\tilde{G}]$ is defined as

$$[\tilde{G}]^T = [\tilde{M}][\tilde{M}]. \quad (15c)$$

Since $[\tilde{G}]$ is always symmetric, Eq. (15b) defines a quadratic form whose extrema are obtained^{16,17} by solving the eigenvalue equations

$$[\tilde{G}]T = \lambda T, \quad (16a)$$

$$\det\{[\tilde{G}] - \lambda[I]\} = 0, \quad (16b)$$

where $[I]$ is the (3×3) identity matrix and the maxima and minima are given by the eigenvalues corresponding to the largest and the smallest eigenvalues, respectively.

(2) Consider now the case $([\tilde{M}]T, \tilde{m}) = \beta \simeq 1$ such that

$$\tilde{R} \simeq \tilde{m} + \beta\tilde{m}; \quad (17a)$$

then

$$\|\tilde{R}\|^2 = (\tilde{R}^T, \tilde{R}) = (1 + \beta)^2 \|\tilde{m}\|^2, \quad (17b)$$

that is, $[\tilde{M}]T$ must be parallel to \tilde{m} , and T must satisfy $[\tilde{M}]T = \beta\tilde{m}$.

B. General Numerical Solution

From Eq. (14b) we obtain

$$\|\tilde{R}\|^2 = \|\tilde{m}\|^2 + 2(\tilde{m}^T, [\tilde{M}]T) + (T^T, [\tilde{G}]T), \quad T^T = 1, \quad (18a)$$

where the first term is independent of T and the other two correspond to the subcases discussed in the previous subsection.

Let us for convenience rewrite Eq. (18a) in the index notation as

$$F = \sum_{ij} a_{ij}x_i x_j + 2b_i x_i + c, \quad \sum_i |x_i|^2 = 1, \quad (18b)$$

where we define

$$a_{ij} = [\tilde{G}], \quad b_i = \tilde{m}^T[\tilde{M}], \quad c = \|\tilde{m}\|^2, \quad x_i = T_i.$$

We are looking for an extremum of F as a function of the x_i terms on a unit sphere. The problem can be visualized as a search for an extremum of a distance from an origin to a displaced ellipsoidal surface. We search for such an extremum according to the following sequence of steps:

(1) Rotate to the principal axis by means of a rotation matrix O , such that

$$F = \sum_{j=1}^3 \lambda_j x_j^2 + 2b_j' x_j + c, \quad b_j' = \sum_{i=1}^3 O_{ij} b_i, \quad j = 1, 2, 3, \quad (18c)$$

where

$$\lambda_j = \sum_{i=1}^3 O_{ij} x_i = \tau = \sum_{i=1}^3 O_{ij} Y_i. \quad (18d)$$

The rotation matrix O_{ij} has the eigenvectors of the matrix a_{ij} as its columns.^{16,17} Note that the rotation does not change the magnitude of the distances and therefore does not affect the sought extrema.

(2) Determining the extrema of F by the method of Lagrange multipliers (μ) results in the inhomogeneous set of linear equations,

$$(\lambda_i - \mu)y_i = b_i', \quad (19a)$$

which, after inversion, gives (with unknown Lagrange multiplier μ and nonzero b_i')

$$y_i = \left(\frac{b_i'}{\lambda_i - \mu} \right). \quad (19b)$$

(3) Substituting Eq. (19b) into the normalization constraint $\sum_i |y_i|^2 = 1$ leads to a sixth-order polynomial equation for μ ,

$$\sum_{i=1}^3 \left(\frac{b_i'}{\lambda_i - \mu} \right)^2 = 1, \quad (20)$$

which (in general) must be solved numerically for the μ values. (For explicit expressions for the polynomial coefficients, in terms of λ_i and b_i' , see Appendix A.) These roots are then substituted into Eq. (19b) to find y_i , the values and into expression (18d) to find the x_i values. Finally, the intensity is computed according to Eq. (13b) for all six roots of Eq. (20); the largest (or smallest) intensity is used to choose the optimal solution.

4. NUMERICAL ILLUSTRATIONS

There have been a number of papers^{3,8-10,18,19} devoted to the derivation of various constraints on the Mueller matrix elements. These constraints are often expressed in terms of bilinear or quadratic inequalities^{18,19} on all 16 elements of the Mueller matrix. In practical terms these constraints amount to the following rule of thumb:

$$|M_{ij}| \leq |M_{11}| < |M_{22}| \sim |M_{33}| < |M_{00}| < 1,$$

$$i, j = 0, 1, 2, 3, \quad i \neq j \quad (21a)$$

based on the Fry-Kattawar inequalities,¹⁹ which are essentially a statement of "ordered diagonal dominance." Also, Barakat¹⁸ has derived the physical realizability condition

$$0 < M_{00} - \left(\sum_i M_{0i}^2 \right)^{1/2} < M_{00} + \left(\sum_i M_{0i}^2 \right)^{1/2} < 1, \quad i = 1, 2, 3. \quad (21b)$$

which constrains energy "gain" to be less than unity.²⁰ Finally, there is another condition for physical realizability of Mueller matrices that ensures that the degree of polarization p of the output beam is less than unity for any input (see the discussion of numerical results, Subsection 4.C).

Our first example corresponds to real experimental data,²⁰ while the second example is purely numerical and is designed to highlight interesting computational features of the optimization procedure. Whereas the first example satisfies all the conditions above, the second satisfies only condition (21b), since it is not quite diagonally dominant.

A. Case 1

Consider the following Mueller matrix, which corresponds to experimental data taken for a combined collimator-radiometer system²⁰ (with a quoted measurement error on the order of 7%):

$$[M] = \begin{bmatrix} 0.7599 & -0.0623 & 0.0295 & 0.1185 \\ -0.0573 & 0.4687 & -0.1811 & -0.1863 \\ 0.0384 & -0.1714 & 0.5394 & 0.0282 \\ 0.1240 & -0.2168 & -0.0120 & 0.6608 \end{bmatrix}.$$

From a numerical point of view, this is quite general: $[M]$ is nonsingular and asymmetric, and $m = 0$. The corresponding vector b_i of Eq. (18a) is given by

$$b_i^T = m^T [M] = [-0.0603 \quad 0.0296 \quad 0.0937].$$

Likewise, the corresponding matrix $[G]$ of Eqs. (15a) and (15c) becomes

$$a_{ij} = [G] = \begin{bmatrix} 0.2961 & -0.1747 & -0.2354 \\ -0.1747 & 0.3239 & 0.0410 \\ -0.2354 & 0.0410 & 0.4722 \end{bmatrix}.$$

In order to diagonalize $[G]$, its eigenvalues are computed as

$$\lambda_1 = 0.0683, \quad \lambda_2 = 0.3358, \quad \lambda_3 = 0.6880,$$

with the corresponding eigenvectors (composing the columns of the rotation matrix O) computed as follows:

$$[O] = \begin{bmatrix} -0.7827 & 0.1872 & -0.5936 \\ -0.4696 & -0.8036 & 0.3556 \\ -0.4086 & 0.5649 & 0.7169 \end{bmatrix}.$$

We note that all the eigenvalues are not only real ($[G]$ is symmetric by construction (15c)) but also positive because $[M]$ in Eq. (15c) is not singular for this case.

The coefficients of the polynomial are computed from Eq. (20) as

$$(1.0000)\mu^6 + (-2.1842)\mu^5 + (1.7814)\mu^4 + (-0.6780)\mu^3 + (0.1221)\mu^2 + (-0.0092)\mu + (0.0002)\mu^0 = 0.$$

For each root of μ , a solution vector was computed by using Eq. (19b), and its intensity was computed by using Eqs. (18b) and (18a). The results are displayed in Table 1, together with the ellipticities and the tilts of the corresponding Stokes vectors used in Fig. 1 below (see Appendix A for further details). The largest intensity value, 0.9677, was used to calculate (by using Eq. (19b)) the corresponding optimal solution, and in Table 2 it is compared with several commonly used Stokes vectors.

Table 1. Roots and Intensities for Case 1

| Root Number | Root μ | Norm $\ \mathbf{x}\ $ | Intensity F | Tilt θ (deg) | Ellipticity ϵ (deg) |
|-------------|------------------|-----------------------|---------------|---------------------|------------------------------|
| 1 | 0.8019 + i0.0000 | 1.0000 | 0.9677 | 75.1 | 24.1 |
| 2 | 0.5739 + i0.0000 | 0.9999 | 0.6942 | -17.2 | -21.0 |
| 3 | 0.3548 + i0.0000 | 0.9970 | 0.5931 | -32.9 | 8.5 |
| 4 | 0.3170 + i0.0000 | 0.9973 | 0.5343 | 44.1 | -24.1 |
| 5 | 0.0734 + i0.0000 | 0.9997 | 0.2759 | 13.7 | 6.6 |
| 6 | 0.0633 + i0.0000 | 0.9999 | 0.2379 | -72.4 | -17.3 |

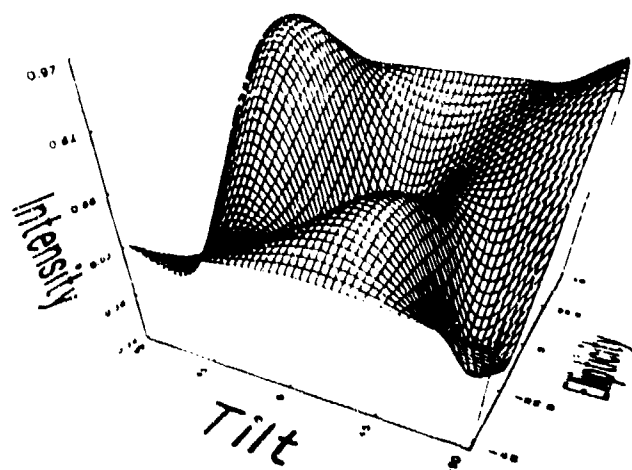


Fig. 1. Polarization dependence of the adjustable intensity. The general topology of the surface is determined by the six stationary points corresponding to the six roots of Eq. (20) with the global maximum at θ (tilt) = 75.1 deg and ϵ (ellipticity) = 24.1 deg and with the global minimum at θ (tilt) = 72.4 deg and ϵ (ellipticity) = -17.3 deg.¹⁴

The polarization dependence of the intensity expressions (18) is illustrated in Fig. 1, in which the adjustable intensity is plotted as a function of ellipticity and tilt¹⁴ as defined by Eqs. (8a) and (8b). Using the optimal Stokes vector [1.0000, -0.5807, 0.3378, 0.7408], we compute the corresponding ellipticity and tilt to be 0.4171 = 24.1 deg and 1.3134 = 75.1 deg,¹⁴ respectively.

It is interesting to note that our maximum value of adjustable intensity (0.9677) exceeds the maximum gain for the total intensity in the beam (calculated to be 0.89 in Ref. 18). This apparently paradoxical result prompted us to check the degree of polarization of the output beam [0.8938, -0.5287, 0.3410, 0.73], which is 1.08. Thus even an experimental Mueller matrix may be slightly unrealizable (the violations are less than 8%, however, and only for an extremely small

part of the Stokes space). We emphasize that the last result is entirely independent of our optimization procedure and probably reflects a slight measurement error.²⁰ Indeed, one need only use Eq. (6) with the optimal Stokes vector to recover the above violation.

B. Case 2

With the example

$$[M] = \begin{bmatrix} 0.1800 & 0.9400 & -0.0100 & -0.0050 \\ 0.2900 & 0.1250 & -0.3100 & -0.0150 \\ -0.0200 & -0.0250 & -0.1600 & -0.3500 \\ 0.0150 & 0.1000 & -0.0800 & -0.1950 \end{bmatrix},$$

we highlight the occurrence of complex roots when the rule of thumb [relation (21a)] is violated [note, however, that relation (21b) is satisfied]. From a numerical point of view, $[M]$ does not appear to be special: it is nonsingular and asymmetric, $\tilde{m} \neq 0$, and $[\tilde{M}]$ is not singular.

As in the previous example, we compute δ^T and $[G]$ for this $[M]$ and use these values to compute the eigenvalues of $[\tilde{G}]$:

$$\lambda_1 = 0.0088, \quad \lambda_2 = 0.0771, \quad \lambda_3 = 0.2292.$$

The associated sixth-order polynomial then becomes

$$(1.0000)\mu^6 + (-0.6302)\mu^5 + (0.1308)\mu^4 + (-0.0100)\mu^3 + (0.0002)\mu^2 + (0.0000)\mu^1 + (0.0000)\mu^0 = 0,$$

which has six (real and complex) roots, as is shown in Table 3. Whereas the norm test shows that the complex roots are valid, they must be ignored, as the solution vector must always be real by the construction of Eqs. (4) and (19b). All numerical experiments have shown the existence of at least two real roots that correspond to the maximum and the minimum of the adjustable intensity. In this case, despite the presence of four complex roots, the extrema are found correctly, and they correspond to the two real roots, as is shown in Table 3.

Table 2. Optimal versus Standard Stokes Vectors for Case 1

| Optimal Case and Examples | Stokes Vector | | | | Intensity |
|---------------------------|---------------|---------|---------|---------|-----------|
| | S_0 | S_1 | S_2 | S_3 | |
| Maximal solution | 1.0000 | -0.5807 | 0.3378 | 0.7408 | 0.9677 |
| Minimal solution | 1.0000 | -0.6720 | -0.4746 | -0.5684 | 0.2379 |
| x polarized | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.4422 |
| y polarized | 1.0000 | -1.0000 | 0.0000 | 0.0000 | 0.6810 |
| Polarized 45 deg from x | 1.0000 | 0.0000 | 1.0000 | 0.0000 | 0.6350 |
| Polarized 135 deg from x | 1.0000 | 0.0000 | -1.0000 | 0.0000 | 0.5337 |
| RHC polarized | 1.0000 | 0.0000 | 0.0000 | 1.0000 | 0.8244 |
| LHC polarized | 1.0000 | 0.0000 | 0.0000 | -1.0000 | 0.5522 |

Table 3. Roots and Powers for Case 2

| Root Number | Root α | Norm α | Intensity F | Tilt θ (deg) | Ellipticity ϵ (deg) |
|-------------|--------------------|---------------|---------------|---------------------|------------------------------|
| 1 | $0.2963 + i0.0000$ | 1.0000 | 0.6815 | -35.1 | -11.7 |
| 2 | $0.1570 + i0.0299$ | 1.0000 | No solution | No solution | No solution |
| 3 | $0.1570 + i0.0299$ | 1.0000 | No solution | No solution | No solution |
| 4 | $0.0093 + i0.0023$ | 1.0000 | No solution | No solution | No solution |
| 5 | $0.0093 + i0.0023$ | 1.0000 | No solution | No solution | No solution |
| 6 | $0.0013 + i0.0000$ | 1.0000 | 0.0000 | -35.9 | -12.8 |

Table 4. Optimal versus Standard Stokes Vectors for Case 2

| Optimal Case and Examples | Stokes Vector | | | | Intensity |
|---------------------------|---------------|---------|---------|---------|-----------|
| | S_0 | S_1 | S_2 | S_3 | |
| Maximal solution | 1.0000 | 0.2944 | -0.8200 | -0.4908 | 0.6815 |
| Minimal solution | 1.0000 | -0.2829 | 0.8570 | -0.4306 | 0.0000 |
| x polarized | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.4324 |
| y polarized | 1.0000 | -1.0000 | 0.0000 | 0.0000 | 0.1857 |
| Polarized 45 deg from x | 1.0000 | 0.0000 | 1.0000 | 0.0000 | 0.1924 |
| Polarized 135 deg from x | 1.0000 | 0.0000 | -1.0000 | 0.0000 | 0.6234 |
| RHC polarized | 1.0000 | 0.0000 | 0.0000 | 1.0000 | 0.4949 |
| LHC polarized | 1.0000 | 0.0000 | 0.0000 | -1.0000 | 0.4960 |

Table 4 shows that the found extrema are well above (or below) the intensity calculated for some commonly used Stokes vectors.

C. Discussion of Numerical Results

Several interesting conclusions can be drawn from our two examples above and from many other numerical experiments. First, explicit constraints on Mueller matrix elements must be derived that ensure that the degree of polarization of the output beam is less than unity for any (normalized) input parameters. Whether these constraints follow directly from the Fry-Kattawar inequalities is still an open question, but our experimentation with Howell's data ($p = 1.08$ for optimal input) seems to point to the contrary.

We note that adjustable-intensity values always seem to be ordered according to the magnitude of the real part of the root. The physics here requires that there exist at least two real roots, which seems indeed to be the case,²¹ even for singular matrices. We also noticed that all six roots turn out to be real when a given matrix is likely to represent accurate experimental data, that is, when it satisfies both relation (21a) and relation (21b). Furthermore, numerical experiments have shown that the maximal adjustable intensity becomes greater than unity (in violation of the passive medium assumption¹⁸) when Barakat's condition is relaxed; however, all six roots seem to remain real.²¹ Finally, when the Fry-Kattawar inequalities¹⁹ are violated, complex roots have been observed on numerous occasions. Thus the appearance of complex roots seems to be linked to the physical realizability of the Mueller matrix and is an interesting subject for further study. Finally, we note that if, say, b_2' in Eq. (19a) is zero, then $\lambda_2 = \mu$, and one should not proceed with Eqs. (19b) and (20) to avoid divergence. In this case Eq. (20) can be reduced to the fourth-order equation. This possibility should be checked whenever μ is numerically close to any one of the three values, especially when the procedure is accompanied by an inaccurate norm test.

5. CONCLUDING REMARKS

One of the major difficulties in dealing with the scattering of partially polarized light is a first-principle calculation of the corresponding Mueller matrix. The calculation is often not easy to interpret physically because it usually involves, for all four Stokes parameters, either an ensemble averaging over a large number of elementary scatterers or a time averaging of a single but time-dependent scatterer. It is the latter temporal view that we considered to be more basic, and we adopted it in this paper. It leads naturally to the use of the Stokes-Mueller formalism based on the polarization coherency matrix approach introduced by Wolf.²

Furthermore, our approach was phenomenological insofar as the Mueller matrix was assumed to be known (measured) from the outset, and then expressions for the adjustable and the total intensities, as functions of transmitted polarizations, were derived. This allowed us to formulate naturally some practical and physically meaningful questions such as the problem of adjustable-intensity optimization, which was solved here (apparently for the first time). In a forthcoming publication, the optimization procedure is generalized to the "polarimetric contrast" case with important applications in optical through millimeter-wave imaging.

The above phenomenological approach must be complemented with a modeling procedure that allows direct construction of Mueller matrices from time sequences of single-scatterer Jones matrices. In this regard, the most recent contribution of Kim *et al.*⁸ seems to be quite promising. We are currently in the process of testing relations developed in Ref. 8 against experimental data.

APPENDIX A: FURTHER NUMERICAL DETAILS

In order to use efficient polynomial root-searching routines from the IMSL scientific software package, we had to rewrite Eq. (20) in the canonical polynomial form $(A_i \mu^{6-i}, i = 0, \dots, 6)$.

Eq. (16). The explicit expressions for A_i in terms of B_i and λ_i (with $B_i \equiv b_i$) are as follows:

$$\begin{aligned} A_0 &= 1, \\ A_1 &= -2(\lambda_1 + \lambda_2 + \lambda_3), \\ A_2 &= (\lambda_1 + \lambda_2 + \lambda_3)^2 + 2(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3) \\ &\quad - (B_1^2 + B_2^2 + B_3^2), \\ A_3 &= -2[\lambda_1\lambda_2\lambda_3 + (\lambda_1 + \lambda_2 + \lambda_3)(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)] \\ &\quad + 2[B_1^2(\lambda_2 + \lambda_3) + B_2^2(\lambda_1 + \lambda_3) + B_3^2(\lambda_1 + \lambda_2)], \\ A_4 &= (\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)^2 + 2[(\lambda_1\lambda_2\lambda_3)(\lambda_1 + \lambda_2 + \lambda_3)] \\ &\quad - [B_1^2(\lambda_2 + \lambda_3)^2 + B_2^2(\lambda_1 + \lambda_3)^2 + B_3^2(\lambda_1 + \lambda_2)^2] \\ &\quad - 2[B_1^2(\lambda_2\lambda_3) + B_2^2(\lambda_1\lambda_3) + B_3^2(\lambda_1\lambda_2)], \\ A_5 &= -2[(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)(\lambda_1\lambda_2\lambda_3)] \\ &\quad + 2[B_1^2(\lambda_2\lambda_3)(\lambda_2 + \lambda_3) + B_2^2(\lambda_1\lambda_3)(\lambda_1 + \lambda_3) \\ &\quad + B_3^2(\lambda_1\lambda_2)(\lambda_1 + \lambda_2)], \\ A_6 &= (\lambda_1\lambda_2\lambda_3)^2 - [B_1^2(\lambda_2\lambda_3)^2 + B_2^2(\lambda_1\lambda_3)^2 + B_3^2(\lambda_1\lambda_2)^2]. \end{aligned}$$

To compute the roots of this polynomial, both the Laguerre method and the Jenkins-Traub method were used (they were in perfect agreement). In addition, the computed roots were substituted back into the original polynomial for an error test. According to the well-known theorem about polynomials with real coefficients, the complex roots always came in conjugate pairs. Although physics demands (and our experiments with numerous cases have shown) at least two real roots, we have no rigorous proof of their existence.

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BASIC CONCEPTS FOR THE DESIGN OF A DUAL POLARIZATION RADAR FOR CLUTTER ANALYSIS

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ABSTRACT

Based on the dual polarization radar, the Kennaugh null polarization theory for a single scatterer has been extended to an ensemble of scatterers (e.g. rain, cloud, terrain, rough surface, etc.). The formulations are developed for the null polarizations in terms of the average scattering matrix elements based on the coherency matrix formulations. Also the variances (i.e., spread and depth) for each null polarization are derived. Further the null polarizations and their statistics are expressed in terms of the average Mueller matrix elements which contain all the polarimetric information about the ensemble of scatterers. The theory developed could be applied to various specific types of hydrometeorologic, sea, vegetation and terrain clutter.

1. INTRODUCTION

In recent years, there has been a rapidly expanding volume of research from both a theoretical and experimental point of view, directed towards the determination of the characteristic properties of the radar clutter, i.e., of scatterers e.g. hydrometeors and rough surfaces through the use of polarization. It has become very important to investigate the properties of the radar clutter for detecting the target in the background of the clutter, discriminating the various kinds of hydrometeorologic particles and studying the dynamic behaviour of the rough surfaces, such as sea surface, vegetation, terrain, etc. This paper will specifically investigate the polarization techniques to determine the clutter characteristics derived for the dual polarization radar.

For the coherent scattering, Kennaugh [1949-54] and Huynen [1970] showed that the complete polarimetric information about the target is contained within a 2×2 complex scattering matrix $[S]$ or in the 4×4 real Mueller matrix. Kennaugh studied the polarization characteristics of the radar echoes and introduced the concept of null polarization theory. According to this theory, there exist a pair of polarization states (co-pol nulls) of the radiation which result zero backscattered power in the co-polarized channel. Similarly there, also exist a pair of polarization states (cross-pol nulls) of the radiation which result zero backscattered power in the cross-polarized channel. These polarizations are termed as null polarizations. The representation of the nulls on the polarization Poincaré sphere give a phenomenological look of the properties such as shape and structure of the object. In the case of clutter, it consists of a random distribution of scatterers and their relative locations cause the random phase fluctuations of each wavelet in the total backscattered field which is the sum of the interference effects of the individual wavelet scattered from each scatterer. Therefore, the scattering matrix elements are replaced by their ensemble averages. Also Kennaugh's null polarization technique is applied for this type of distributed target and thus the properties of the clutter are investigated in terms of the null polarizations.

First the polarimetric model for a single target in which the returned signal is completely polarized will be developed and then it will be extended for a distributed target in which the returned signal is partially polarized.

2. POLARIMETRIC SINGLE TARGET MODEL

The returned signal from a single target is always completely polarized. The target model can be developed by using the scattering matrix.

(a) The Scattering Matrix

It was first shown by Sinclair [1950] that a radar target acts like a polarization transformer which is described by its associated scattering matrix [S]. At the target scatterer, the target scattering matrix characterizes the scattering properties of the target such that the scattered electric field can be related to the incident electric field by:

$$\begin{bmatrix} E_{S1} \\ E_{S2} \end{bmatrix} = \frac{e^{-jk_0 r}}{r} \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} E_{i1} \\ E_{i2} \end{bmatrix} \quad (1)$$

For monostatic and reciprocal radar system, $S_{12} = S_{21}$ and the [S] becomes symmetric. S_{11} , S_{12} and S_{22} are complex parameters. The relative scattering matrix is given by:

$$[S]_{\text{SMR}} = \begin{bmatrix} |S_{11}|e^{j(\phi_{11}-\phi_{12})} & |S_{12}| \\ |S_{12}| & |S_{22}|e^{j(\phi_{22}-\phi_{12})} \end{bmatrix} \quad (2)$$

Throughout the remaining discussion, it will be assumed that the [S] implies the monostatic $[S]_{\text{SMR}}$ case. Thus we find that [S] contains five independent real values.

(b) Null Polarizations

Null polarizations represent those polarization states which result zero return in the receiving channels. If the zero return is in the co-polarized channel, it is termed as co-pol null. If the zero return is in the cross-polarized channel, it is termed as cross-pol null.

In order to obtain null polarizations, the scattering matrix given in equation (1) can be transformed to another polarization base by the following expression:

$$[S'] = [T]^T [S] [T] \quad (3)$$

where

$$[T] = \frac{1}{(1 + \rho\rho^*)^{1/2}} \begin{bmatrix} 1 & -\rho^* \\ \rho & 1 \end{bmatrix}$$

where ρ is the polarization ratio of the signal. Substituting equation (1) into (3), we get

$$\begin{aligned}
S'_{11} &= (1 + \rho\rho^*)^{-1} (\rho^2 S_{22} + 2\rho S_{12} + S_{11}) \quad , \\
S'_{12} &= (1 + \rho\rho^*)^{-1} [\rho S_{22} + (1 - \rho\rho^*) S_{12} - \rho^* S_{11}] \quad , \\
S'_{21} &= S'_{12} \quad , \\
S'_{22} &= (1 + \rho\rho^*)^{-1} (\rho^{*2} S_{11} - 2\rho^* S_{12} + S_{22}) \quad .
\end{aligned} \tag{4}$$

In vector form:

$$\begin{bmatrix} E'_{S1} \\ E'_{S2} \end{bmatrix} = \begin{bmatrix} S'_{11} & S'_{12} \\ S'_{12} & S'_{22} \end{bmatrix} \begin{bmatrix} E'_{i1} \\ E'_{i2} \end{bmatrix} \quad .$$

Let E'_{i1} be transmitted and $E'_{i2}=0$, then for co-pol nulls $E'_{S1}=0$. Thus we get co-pol and cross-pol nulls, respectively, as follows [Boerner, et al., 1981]:

$$\rho_{co} = \frac{-S_{12} \pm (S_{12}^2 - S_{11}S_{22})^{1/2}}{S_{22}} \quad , \tag{5}$$

$$\rho_x = \frac{-B \pm (B^2 - 4AC)^{1/2}}{2A} \tag{6}$$

where

$$A = S_{22} S_{12}^* + S_{11}^* S_{12} \quad ,$$

$$B = -(|S_{11}|^2 - |S_{22}|^2) \quad ,$$

$$C = -A^* \quad .$$

The graphical representation of the null polarization states for a single target is shown in Fig. 1. The detailed analysis on this section is given in [A.P. Agrawal and W.M. Boerner, April 14 (#APA-1) and May 15 (#APA-2), 1985].

3. POLARIMETRIC CLUTTER TARGET MODEL

The returned signal from a distributed target (rain, sea surface, terrain, fog, etc.) is always partially polarized. The partially polarized signal is represented by the coherency matrix or Stokes vector.

(a) Coherency Matrix

The backscattered coherency matrix of the backscattered signal is defined [Born & Wolf, 1964] as

$$[J_S] = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} = \begin{bmatrix} \langle E_{s1} E_{s1}^* \rangle & \langle E_{s1} E_{s2}^* \rangle \\ \langle E_{s2} E_{s1}^* \rangle & \langle E_{s2} E_{s2}^* \rangle \end{bmatrix} \tag{7}$$

$$= \langle \mathbf{E}_s \mathbf{E}_s^* \rangle \quad (8)$$

$$= \langle [\mathbf{S}] \mathbf{E}_i \mathbf{E}_i^* [\mathbf{S}]^* \rangle \quad (9)$$

$$\text{Tr}(\mathbf{J}) = J_{11} + J_{22} \quad (10)$$

$$\det(\mathbf{J}) = J_{11}J_{22} - |J_{12}|^2 \geq 0$$

$\text{Tr}(\mathbf{J})$ and $\det(\mathbf{J})$ are the invariants to the transformation or rotation of the polarization basis.

The degree of coherency:

$$\mu = |\mu| e^{j\beta} = \frac{J_{12}}{(J_{11}J_{22})^{1/2}} \quad ; \quad J_{12} = J_{21}^* \quad (11)$$

The degree of polarization:

$$P = \left(1 - \frac{4\det(\mathbf{J})}{(J_{11} + J_{22})^2} \right)^{1/2} \quad (12)$$

$P = 1$ for completely polarized signal,

$P = 0$ for unpolarized signal, and

$0 < P < 1$ for partially polarized signal.

(b) Null Polarizations for Partially Polarized Backscattered Signals

The null polarizations, i.e., co-pol and cross-pol nulls can be calculated for distributed targets using the coherency matrix. The derivation is given below.

The backscattered coherency matrix $[\mathbf{J}_s]$ can be transformed into the null polarization base as:

$$[\mathbf{J}'_s] = \begin{bmatrix} \langle \mathbf{E}'_{s1} \mathbf{E}'_{s1}^* \rangle & \langle \mathbf{E}'_{s1} \mathbf{E}'_{s2}^* \rangle \\ \langle \mathbf{E}'_{s2} \mathbf{E}'_{s1}^* \rangle & \langle \mathbf{E}'_{s2} \mathbf{E}'_{s2}^* \rangle \end{bmatrix} \quad (13)$$

The coherency matrix parameters in terms of scattering matrix elements in the null polarization base can be derived from equation (9). Substituting $\mathbf{E}'_{i1}=1$, $\mathbf{E}'_{i2}=0$ in equation (9), we get:

$$\begin{aligned} J'_{s11} &= \langle |\mathbf{S}'_{11}|^2 \rangle \\ J'_{s12} &= \langle \mathbf{S}'_{11} \mathbf{S}'_{12}^* \rangle \\ J'_{s21} &= J'_{s12}^* \\ J'_{s22} &= \langle |\mathbf{S}'_{12}|^2 \rangle \end{aligned} \quad (14)$$

According to McCormick and Hendry [1976, 1985] and Poelman [1976], the null polarizations can be calculated by keeping $J'_{s12}=0$.

$$J'_{s12} = \langle \sum_{i=1}^N E'_{s1i} E'_{s2i} \rangle = 0 \quad (15)$$

$\Sigma \Rightarrow$ for ensemble of particles.

From equations (14) and (15)

$$J'_{s12} = \langle \sum_{i=1}^N S'_{11i} S'_{12i*} \rangle = 0 \quad (16)$$

Substituting Eq. (3) into Eq. (16), we get

$$J'_{s12} = \langle \Sigma (1 + \rho\rho^*)^{-2} (S_{11i} + \rho^2 S_{22i} + 2\rho S_{12i}) (-\rho S_{11i}^* + \rho^* S_{22i}^* + (1 - \rho\rho^*) S_{12i}^*) \rangle = 0$$

or,

$$\langle \sum_i (\rho A_i + B_i) (-\rho B_i^* + A_i^*) \rangle = 0 \quad (17)$$

where

$$A_i = \rho S_{22i} + S_{12i}$$

$$B_i = \rho S_{12i} + S_{11i}$$

or

$$\langle -\rho^2 \sum_i A_i B_i^* + \rho \sum_i (|A_i|^2 - |B_i|^2) + \sum_i A_i^* B_i \rangle = 0 \quad (18)$$

Now the time average is replaced by the ensemble average and the equation (18) becomes

$$-\rho^2 \overline{AB^*} + \rho (\overline{|A|^2} - \overline{|B|^2}) + \overline{A^* B} = 0 \quad (19)$$

Let

$$Q = \overline{AB^*} \quad ,$$

$$R = \overline{|A|^2} - \overline{|B|^2} \quad .$$

Hence, equation (19) is

$$\rho^2 Q - \rho R - Q^* = 0 \quad (20)$$

$$\rho = \frac{R \pm (R^2 + 4QQ^*)^{1/2}}{2Q} \quad (21)$$

$$= \frac{(\overline{|A|^2} - \overline{|B|^2}) \pm [(\overline{|A|^2} - \overline{|B|^2})^2 + 4|\overline{AB^*}|^2]^{1/2}}{2\overline{AB^*}} \quad (22)$$

Thus,

$$\rho_x = \frac{\overline{|A|^2}}{\overline{AB^*}} - \frac{(\overline{|A|^2} \overline{|B|^2} - |\overline{AB^*}|^2)}{\overline{AB^*} (\overline{|A|^2} + \overline{|B|^2})} \quad (23)$$

$$\rho_{co} = -\frac{\overline{|B|^2}}{\overline{AB^*}} + \frac{(\overline{|A|^2} \overline{|B|^2} - |\overline{AB^*}|^2)}{\overline{AB^*} (\overline{|A|^2} + \overline{|B|^2})} \quad (24)$$

Neglecting the second term in RHS in equations (23) and (24), we get

$$\rho_x \cong \frac{\overline{|A|^2}}{\overline{AB^*}} \cong \frac{\overline{A^*}}{\overline{B^*}} \quad (25)$$

$$\rho_{co} \cong -\frac{\overline{|B|^2}}{\overline{AB^*}} \cong -\frac{\overline{B}}{\overline{A}} \quad (26)$$

Co-Pol Nulls:

From equation (26), let $\rho_{co} = \rho$.

$$\rho \overline{A} + \overline{B} = 0 \quad ,$$

$$\rho(\rho \overline{S_{22}} + \overline{S_{12}}) + \rho \overline{S_{12}} + \overline{S_{11}} = 0 \quad ,$$

$$\rho^2 \overline{S_{22}} + 2\rho \overline{S_{12}} + \overline{S_{11}} = 0 \quad .$$

$$\rho_{co} = \frac{-\overline{S_{12}} \pm (\overline{S_{12}}^2 - \overline{S_{11}} \overline{S_{22}})^{1/2}}{\overline{S_{22}}} \quad (27)$$

Cross-Pol Nulls:

From equation (25), let $\rho_x = \rho$,

$$\rho \overline{B^*} = \overline{A^*} \quad ,$$

$$\rho(\rho^* \overline{S_{12}^*} + \overline{S_{11}^*}) = \rho^* \overline{S_{22}^*} + \overline{S_{12}^*} \quad .$$

$$|\rho|^2 \overline{S_{12}^*} + \rho \overline{S_{11}^*} - \rho^* \overline{S_{22}^*} - \overline{S_{12}^*} = 0 \quad (28)$$

Taking the conjugate of equation (28) gives,

$$|\rho|^2 \overline{S_{12}} + \rho^* \overline{S_{11}} - \rho \overline{S_{22}} - \overline{S_{12}} = 0 \quad (29)$$

From equations (28) and (29), we get,

$$\overline{\rho}_x = \frac{-\overline{B} \pm (\overline{B}^2 - 4\overline{A}\overline{C})^{1/2}}{2\overline{A}} \quad (30)$$

where,

$$\overline{A} = (\overline{S_{22}} \overline{S_{12}^*} + \overline{S_{11}^*} \overline{S_{12}}) \quad ,$$

$$\overline{B} = (\overline{S_{22}}^2 - \overline{S_{11}}^2) \quad ,$$

$$\overline{C} = -\overline{A^*} \quad .$$

Comparing Eqs. (5), (6), (7) and (30), it is clear that the average values of the null polarizations for the partially polarized backscattered radiation is the same as those of the completely polarized case except that the scattering matrix parameters are ensemble averages. This has also been shown by McCormick and Hendry [1985].

(c) Mean and Variances of the Null Polarizations

The returns from a distributed target when null polarizations are transmitted are minima rather than zero. For a single target, the returns are zero. Thus the minima are described by the mean, spread and depth of the null polarizations.

(c.1) mean values

The mean values of the null polarizations are $\bar{\rho}_{co}$ and $\bar{\rho}_x$, as given by equations (27) and (28), respectively. The mean values are represented by the four points on the surface of the Poincaré sphere as shown in Fig. 2.

(c.2) spread

The spread of the null polarizations on the Poincaré sphere are derived below:

$$\text{Tr}(J'_s) = J'_{s11} + J'_{s22} \quad (31)$$

$$\det(J'_s) = J'_{s11} J'_{s22} - |J'_{s12}|^2 \quad (32)$$

For co-pol nulls, J'_{s11} is minimum, so $J'_{s11}{}^2$ can be neglected and hence, from equations (31) and (32), we have

$$J'_{s11} \cong \frac{\det(J'_s) + |J'_{s12}|^2}{\text{Tr}(J'_s)} \quad (33)$$

The minima in J'_{s11} can be sensed by going to adjacent polarizations where J'_{s12} is non-zero. Thus equation (33) yields:

$$|J'_{s12}| \cong [\det(J'_s)]^{1/2} \quad (34)$$

Similarly, for cross-pol nulls, where J'_{s22} is minimum, we have

$$|J'_{s12}| \cong [\det(J'_s)]^{1/2} \quad (35)$$

From equations (34), (35) and (16), the expressions for spread for both the co-pol and cross-pol nulls are given by

$$\sigma_{co} = \sigma_x \cong \frac{1}{2} (1-p^2)^{1/2} \quad (36)$$

The same results are found in McCormick and Hendry [1985].

(c.3) depth

The depth for co-pol and cross-pol nulls are defined as below [McCormick and Hendry, 1985]

$$\text{co-pol nulls:} \quad d_{co} = \left[\frac{J_{s11}}{\text{Tr}(J'_s)} \right]_{\min} \cong \frac{\det(J'_s)}{[\text{Tr}(J'_s)]^2} \quad (37)$$

$$\text{cross-pol nulls:} \quad d_x = \left[\frac{J_{s22}}{\text{Tr}(J'_s)} \right]_{\min} \cong \frac{\det(J'_s)}{[\text{Tr}(J'_s)]^2} \quad (38)$$

From equations (37) and (38), we can write:

$$d_{co} = d_x = \frac{1 - p^2}{4} \quad (39)$$

(c.4) degree of polarization for null polarizations

The degree of polarization P is defined by Eq. (12). The value of P will be different for all the four null polarizations, namely \bar{p}_{1co} , \bar{p}_{2co} , \bar{p}_{1x} , and \bar{p}_{2x} . The corresponding degree of polarization can be represented by P_{1co} , P_{2co} , P_{1x} , and P_{2x} . Thus the spread and depth for each null polarization can be rewritten as:

$$\begin{aligned} \text{Spread: } \sigma_{1co} &\equiv (1/2)(1 - p_{1co}^2)^{1/2}, & \sigma_{2co} &\equiv (1/2)(1 - p_{2co}^2)^{1/2} \\ \sigma_{1x} &\equiv (1/2)(1 - p_{1x}^2)^{1/2}, & \sigma_{2x} &\equiv (1/2)(1 - p_{2x}^2)^{1/2} \end{aligned} \quad (40)$$

$$\begin{aligned} \text{Depth: } d_{1co} &\equiv (1 - p_{1co}^2)/4, & d_{2co} &\equiv (1 - p_{2co}^2)/4 \\ d_{1x} &\equiv (1 - p_{1x}^2)/4, & d_{2x} &\equiv (1 - p_{2x}^2)/4 \end{aligned} \quad (41)$$

The theoretical representation of null polarizations for distributed targets are shown on the Poincaré sphere in Fig. 2. The mean values lie on a great circle. The cross-pol nulls are orthogonal and they may bisect the co-pol nulls. The mean values may represent an averaged single target. The spread and depth of the nulls may represent the random nature of the distributed target. For different types of distributed targets, the mean, spread and depth of the null polarizations will have different values on the Poincaré sphere.

(d) Null Polarizations in Terms of Average Mueller Matrix Elements

(d.1) average Mueller Matrix

It is shown by Kennaugh [1949-1954] and Huynen [1970] that the backscattered partially polarized wave can also be represented in terms of the 4x1 Stokes vector and the modified average Mueller matrix $[\bar{M}_m]$ as:

$$g_m^s = [\bar{M}_m] g_m^i \quad (42)$$

where

$$g_m = \begin{bmatrix} g_{m0} \\ g_{m1} \\ g_{m2} \\ g_{m3} \end{bmatrix} = \begin{bmatrix} \langle |E_1|^2 \rangle \\ \langle |E_2|^2 \rangle \\ 2\text{Re}\langle E_1 E_2^* \rangle \\ 2\text{Im}\langle E_1 E_2^* \rangle \end{bmatrix}$$

$$[\bar{M}_m] = [M_{ij}, i=1,4; j=1,4]$$

\mathbf{g}_m^s and \mathbf{g}_m^i are the modified Stokes vectors of the scattered (partially polarized) and the incident (completely polarized) waves. $[\bar{M}_m]$ is a 4×4 real matrix. For a single target \mathbf{g}_m^s represents completely polarized backscattered signal and $[\bar{M}_m]$ is replaced by the coherent Mueller matrix $[M_m]$. In general, $[\bar{M}_m]$ is the time averaged of the $[M_m]$, i.e.,

$$[\bar{M}_m] = \langle [M_m] \rangle \quad (43)$$

$[M_m]$ has five independent parameters and it has one-to-one correspondence with the complex scattering matrix $[S]$. On the other hand, $[\bar{M}_m]$ has nine independent parameters and according to Huynen's distributed target decomposition theorem (Huynen, 1970), a general distributed target can be decomposed as:

$$[\bar{M}_m(9)] = [M'_m(5)] + [\Delta M(4)] \quad (44)$$

where $[M'_m(5)]$ represents an averaged single target and ΔM represents the residue target (e.g. the random behavior of the distributed target).

The matrix $[M_m]$ in terms of the scattering matrix elements can be written as follows (Boerner, et al, 1981):

$$[\bar{M}_m] = \begin{bmatrix} \overline{|S_{11}|^2} & \overline{|S_{11}|^2} & \overline{\text{Re}(S_{11}S_{12}^*)} & \overline{\text{Im}(S_{11}S_{12}^*)} \\ \overline{|S_{12}|^2} & \overline{|S_{22}|^2} & \overline{\text{Re}(S_{12}S_{22}^*)} & \overline{-\text{Im}(S_{12}S_{22}^*)} \\ 2\overline{\text{Re}(S_{11}S_{12}^*)} & 2\overline{\text{Re}(S_{12}S_{22}^*)} & \overline{\text{Re}(S_{11}S_{22}^* + S_{12}S_{12}^*)} & \overline{-\text{Im}(S_{11}S_{22}^* - S_{12}S_{22}^*)} \\ 2\overline{\text{Im}(S_{11}S_{12}^*)} & 2\overline{\text{Im}(S_{12}S_{22}^*)} & \overline{\text{Im}(S_{11}S_{22}^* + S_{12}S_{12}^*)} & \overline{\text{Re}(S_{11}S_{22}^* - S_{12}S_{12}^*)} \end{bmatrix} \quad (45)$$

(d.2) calculation of null polarizations

To calculate the mean values of the co-pol and cross-pol nulls from the average Mueller matrix elements, we assume,

$$[\bar{M}_m] \equiv [M'_m] = [\bar{S}] \quad (46)$$

Hence, the average scattering matrix elements in terms of the average Mueller matrix elements are given by (Boerner, et al, 1981):

$$\begin{aligned} \overline{|S_{11}|} &\equiv (M_{11})^{1/2}, & \phi_{11} &= \phi_{12} - \tan^{-1}(M_{14}/M_{13}) \\ \overline{|S_{12}|} = \overline{|S_{21}|} &\equiv (M_{12})^{1/2}, & \phi_{12} &= \phi_{21} \text{ is arbitrary (may be equal to zero)} \\ \overline{|S_{22}|} &\equiv (M_{22})^{1/2}, & \phi_{22} &= \phi_{12} - \tan^{-1}(M_{42}/M_{32}) \end{aligned} \quad (47)$$

Substituting equation (47) into equations (27) and (30), the mean values of co-pol and cross-pol nulls can be calculated.

To calculate the clusterings of the null polarizations (e.g. spread and depth), the degree of polarization, P , is calculated for each of the co-pol and cross-pol nulls as given below:

Let p_i , $i=1,4$ represents the polarization ratio of the i^{th} mean polarization null (co-pol nulls: p_1, p_2 ;

cross-pol nulls: ρ_1, ρ_4). The normalized spherical coordinates of the point p_i on the Poincaré sphere are given by

$$\begin{aligned} \theta_i &= \cos^{-1} \frac{|U_i|^2 - 1}{|U_i|^2 + 1} \\ \phi_i &= 2\phi_i = -\tan^{-1} \frac{\text{Im}(U_i)}{\text{Re}(U_i)} \end{aligned} \quad (48)$$

where

$$U_i = \frac{1 - jp_i}{1 + jp_i}$$

The normalized Stokes vector parameters can be written as

$$g_{mi} = \begin{bmatrix} g_{m0} \\ g_{m1} \\ g_{m2} \\ g_{m3} \end{bmatrix} = \begin{bmatrix} .5(1 + x_i) \\ .5(1 - x_i) \\ y_i \\ -z_i \end{bmatrix} \quad (49)$$

where x_i , y_i , and z_i are given by,

$$\begin{aligned} x_i &= \sin\theta_i \cos\phi_i \\ y_i &= \sin\theta_i \sin\phi_i \\ z_i &= \cos\theta_i \end{aligned}$$

Thus the incident Stokes vector can be calculated for each of $\rho_1 = \bar{\rho}_{1co}$, $\rho_2 = \bar{\rho}_{2co}$, $\rho_3 = \bar{\rho}_{1x}$, and $\rho_4 = \bar{\rho}_{2x}$ from (48) and (49). Using equation (42) the scattered Stokes vector can be calculated for ρ_i . Hence, the degree of polarization, P , is given by

$$P = \left(\frac{(g_{m0} - g_{m1})^2 + g_{m2}^2 + g_{m3}^2}{(g_{m0} + g_{m1})^2} \right)^{1/2} \quad (50)$$

Thus P_{1co} , P_{2co} , P_{1x} , and P_{2x} are calculated. The co-pol and cross-pol null clusterings are found from equations (40) and (41).

Thus, if the average Mueller matrix for the clutter is given, a complete polarimetric clutter model can be described by null polarizations and their statistics on the Poincaré sphere.

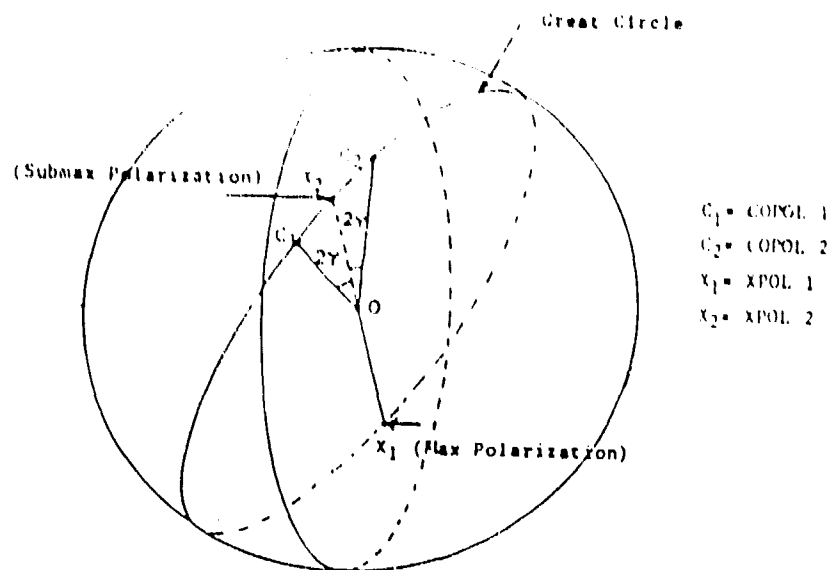


Figure 1 Representation of null polarizations for a single target on the Poincaré sphere.

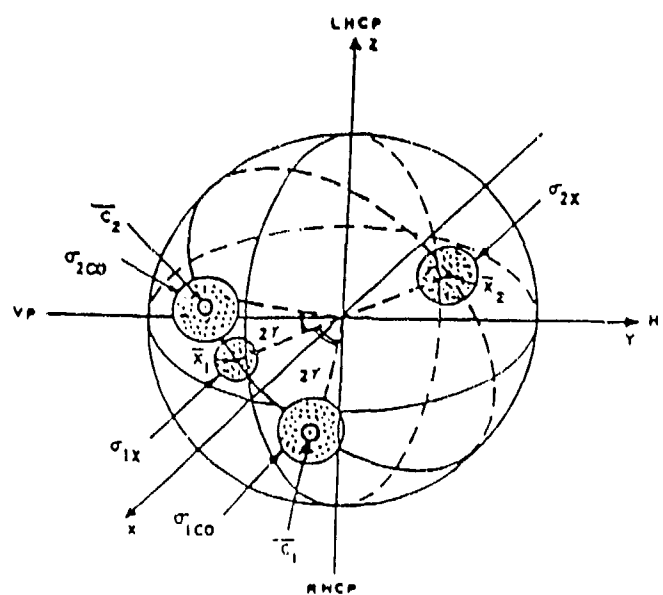


Figure 2 Theoretical representation of null polarizations for a distributed target on the Poincaré sphere.

4. CONCLUSION

In this paper, we have seen that the polarization nulls (co-pol and cross-pol) for the clutter target are represented by the four small statistical regions on the polarization Poincare sphere. The regions are defined by the average values and their variances i.e., the depth and the spread. It is well known that the partially polarized backscattered signal can be decomposed into two components - completely polarized (coherent) and unpolarized (incoherent). The former may be considered the backscattering from an average part of the clutter (or equivalent to the average single target) and the latter from the incoherent part of the clutter. Since the polarization nulls for a single target are represented by the four points on the surface of a sphere as shown in Fig. 1, the average values of the polarization nulls and their variances would represent an average part and the incoherent part of the clutter, respectively. From Section 3, it is clear that the spread and the depth are dependent on the degree of polarization and thus, on the degree of randomness of the multiple scatterers. The spread and the depth are increased with the clutter in a more random nature. It can be pointed out that all the clustering regions may not have the same variances for the clutter and the values of the mean, spread and depth may vary from clutter type to clutter type. Therefore, based on this fact, a classification scheme for the clutter versus clutter could be framed out based on the null polarization theory.

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DESCRIPTION OF A MONOSTATIC POLARIMETRIC RADAR MODEL FOR FLUCTUATING
DISTRIBUTED SCATTERERS WITH APPLICATIONS TO RAIN BACKSCATTER

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ABSTRACT

The polarimetric backscatter from fluctuating distributed scatterers is modeled, and the coherency matrix and its properties are used to formulate the Kennaugh target characteristic polarization theory for the time-dependent distributed scatterer case. The simplified descriptive theory of such type of clutter here developed is applied to a rain backscatter model for extracting information about such rain parameters as the mean canting angle and the drop shape. The Aitoff-Hammer Equal Area Projection of the Poincaré sphere is introduced to demonstrate the effective representation of the clustering of the characteristic polarization states resulting from time-sequential measurements of such fluctuating scatterers.

I INTRODUCTION

In recent years, there has been a rapidly expanding volume of research from both a theoretical and experimental point of view, directed toward the

determination of the characteristic properties of distributed fluctuating scatterers, e.g., hydrometeors and moving rough surfaces through the use of polarization. This radar polarimetric approach has become important in order to investigate in detail the polarimetric clustering properties of the time-sequential scattering matrix measurements of distributed scatterers for studies in the detection of targets in the background of such clutter.

For the coherent scattering case, the characteristic polarization state theory for the applications in radar object classification and identification has been studied extensively in [Kennaugh, 1949-54; Huynen, 1970; Boerner et al., 1981; Mieras, 1983; Davidovitz and Boerner, 1986; McCormick and Hendry, 1985; Kostinski and Boerner, 1986; Van Zyl et al., 1986; Agrawal and Boerner, 1987]. The coherent polarization state theory has recently been extended by Nespor, Agrawal and Boerner [1985] and McCormick and Hendry [1985] to the partially coherent case, i.e., for describing polarimetric backscatter of fluctuating distributed scatterers such as rain. In this case, it is found that the COPOL and XPOL Nulls produce minimum returns in the co- and cross-polarized channels rather than zeroes. Thus additional polarization parameters have to be defined for these minima describing the clustering properties associated with fluctuating polarimetric radar returns in terms of the mean clutter COPOL/XPOL Nulls and their spreads. To a certain extent these problems were solved in [McCormick and Hendry, 1985], but still the concept of the mean characteristic polarization states in the case of such distributed fluctuating scatterers has not been brought out very clearly. Therefore, based upon this background, the characteristic polarization state theory has been reformulated, updated and extended to the analysis of distributed fluctuating scatterers using the coherency density matrix approach as also outlined in [Kostinski, James, and Boerner, 1988].

II. THEORY OF DUAL-POLARIZATION RADAR MEASUREMENTS OF DISTRIBUTED FLUCTUATING SCATTERERS

Distributed fluctuating scatterers here constitute a distributed target. The return signal is the result of the interference of all the signals scattered from each scatterer. Due to the relative motion of the scattering centres, and the variations of the size, shape and orientation angles of non-spherical scatterers, the returned power fluctuates with time. Therefore, when the measurements are taken in a sufficient time interval exceeding the decorrelation time, the average power from such distributed fluctuating scatterers can be obtained using the coherency density matrix approach [Atlas, 1964], whereas if measurements are conducted well under the scattering center reshuffling time, the measurements assume coherent characteristics such that for the summation of time-sequential measurements of such quasi-coherent scattering matrices, the concept of time-sequential ensemble averaging of individual "snapshot-coherent" scattering matrices may be used as we are going to introduce in this paper. The decorrelation time (τ) can be related to the rearrangement of scatterers with respect to each other. [Atlas, 1964] defined the decorrelation time for hydrometeors using an autocorrelation function for the gaussian Doppler spectrum with f_t denoting the frequency of the transmitted wave by

$$\tau(\text{ms}) = 51.3/f_t \text{ (GHz)} , \quad (1)$$

where eq. (1) assumes a gaussian Doppler spectrum with the autocorrelation coefficient of 0.01, the root mean square phase shift of 2.14 (radians), and the standard deviation of 100 cm/s.

If polarization switching during successive pulses is accomplished far below τ , the particles can be considered spatially stationary with respect to one

another. Thus the signal received within such a "snapshot" measurement may be considered completely polarized depending upon the degree of polarization of the incident wave [Kostinski, James, and Boerner, 1988]. If, however, electronic switching cannot be done below the decorrelation time of the scatterers, the scatterers are considered spatially non-stationary with respect to one another. Consequently, the received signals become partially polarized. Therefore, in the case where the measurements are performed below the decorrelation time, the coherent polarization theory as given in [Agrawal and Boerner, 1987] can be applied to determine the COPOL and XPOL Nulls. On the other hand, for the cases in which the measurements are not performed below the decorrelation time, the concept of partially polarized waves must be considered, and based upon those properties, the concept of the mean characteristic polarization states and their spread must be used in a time-sequential ensemble averaging sense.

III. RELEVANT PROPERTIES OF PARTIALLY POLARIZED WAVES

A partially polarized wave can be represented by the coherency density matrix [Born and Wolf, 1964] as

$$[J] = \langle \underline{E}_s \otimes \underline{E}_s^* \rangle \quad (2a)$$

where, \underline{E}_s is the scattered field being a function of the incident field \underline{E}_i , and related via the 2x2 complex scattering matrix [S] as $\underline{E}_s = [S]\underline{E}_i$. The symbols $\langle \rangle$ and \otimes denote the time average and the direct product, respectively. Expanding Eq. (2a), we obtain

$$[J] = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} = \begin{bmatrix} \langle E_{s1} E_{s1}^* \rangle & \langle E_{s1} E_{s2}^* \rangle \\ \langle E_{s2} E_{s1}^* \rangle & \langle E_{s2} E_{s2}^* \rangle \end{bmatrix} \quad (2b)$$

where E_{s1} and E_{s2} are the orthogonally polarized components of the vector \underline{E}_s .

The diagonal elements of $[J]$ are real and represent the intensities of the components in the two orthogonal polarization channels (1,2). The off-diagonal elements are complex and they are the conjugate of each other (i.e., $J_{12}=J_{21}^*$) and they satisfy the definition of a Hermitian matrix, $[J]=[J]^*T$, with the superscript T symbolizing the transpose).

The trace, $\text{Tr}[J]$, i.e., the sum of the diagonal elements of the coherency matrix, is equal to the total intensity or the total backscattered power of the received signal and is given by,

$$\text{Tr}[J] = J_{11} + J_{22} \quad (3a)$$

The determinant of $[J]$, which is non-negative, is defined by

$$\det[J] = J_{11}J_{22} - J_{12}J_{21} \geq 0 \quad (3b)$$

Both the $\text{Tr}[J]$ and $\det[J]$ are invariant under rotation transformations.

The degree of coherence or the complex correlation factor is defined as

$$\mu = |\mu|e^{j\beta} = J_{12}/(J_{11}J_{22})^{1/2} ; \quad J_{12} = J_{21}^* \quad (4)$$

where, $|\mu| \leq 1$, and μ is a measure of the correlation between the orthonormal components of the electric field vector.

The degree of polarization, P , is defined as the ratio of the intensity of the polarized part of the wave to the total intensity of the wave and is given [Born and Wolf, 1964] by

$$P = \left(1 - \frac{4\det(J)}{(J_{11}+J_{22})^2} \right)^{1/2} \quad (5)$$

where $0 \leq P \leq 1$. When $P=1$, the wave is said to be completely polarized (CP); for $P=0$, the wave is completely unpolarized (UP); and for $0 < P < 1$, the wave is called partially polarized (PP). The degree of polarization P and the complex correlation factor μ are related [Born and Wolf, 1964] by

$$1-P^2 = \frac{4J_{11}J_{22}}{(J_{11}+J_{22})^2} (1-|\mu|^2) \quad (6)$$

IV. DETERMINATION OF KENNAUGH'S MEAN CHARACTERISTIC POLARIZATION STATES AND THEIR SPREAD FOR DISTRIBUTED FLUCTUATING SCATTERERS

Consider the time-sequential measurements of distributed fluctuating scatterers by a coherent dual-polarization pulsed radar. The radar transmits pulses of the horizontal (H) and vertical (V) polarization states, respectively, and for this pair of pulses the relative phases of the polarimetric scattering matrix $[S(HV)]$

within the decorrelation time of distributed scatterers as defined by eq. (1) are recorded as shown in [Agrawal, 1986]. For the successive time-sequential N pairs of pulses, the scattering matrices are measured, where each scattering matrix may represent a slightly different distribution of the individual fluctuating scatterers.

IV.1 The Characteristic Polarization States for the Coherent i -th Time Sequential Measurement

First, we consider the i -th scattering matrix $[S_i(HV)]$ measured with the i -th pair of pulses. In this case, the backscattered voltages can be given [Kostinski and Boerner, 1986] by the expressions derived for the coherent case as

$$V_{ci} = \underline{h}_r^T [S_i(HV)] \underline{h}_t, \quad V_{xi} = \underline{h}_{r\perp}^T [S_i(HV)] \underline{h}_t \quad (7)$$

where for the i -th scattering matrix measurement, V_{ci} and V_{xi} are the returned voltages in the co-polarized and the cross-polarized channels, respectively; $[S_i(HV)]$ is the scattering matrix; \underline{h}_t and \underline{h}_r are the polarization states of the transmitting and receiving antennas, respectively; and $\underline{h}_{r\perp}$ is the polarization state orthonormal to \underline{h}_r . The normalized polarization state vectors \underline{h}_t and \underline{h}_r (with unit intensity, $|\underline{h}|^2=1$) in the HV basis can be written [Agrawal and Boerner, 1987] as

$$\underline{h}_t(HV) = \frac{1}{\sqrt{1+\rho\rho^*}} \begin{bmatrix} 1 \\ \rho \end{bmatrix}, \quad \underline{h}_r(HV) = \frac{1}{\sqrt{1+\kappa\kappa^*}} \begin{bmatrix} 1 \\ \kappa \end{bmatrix}, \quad \underline{h}_{r\perp}(HV) = \frac{1}{\sqrt{1+\kappa\kappa^*}} \begin{bmatrix} -\kappa^* \\ 1 \end{bmatrix} \quad (8)$$

where ρ and κ represent the polarization ratios of the transmitting and receiving antennas, respectively.

Substituting eq. (8) into eq. (7), the voltage equations are given by

$$V_{ci} = [(1+\kappa\kappa^*)(1+\rho\rho^*)]^{-1/2} (\kappa\rho S_{VV_i} + (\rho+\kappa)S_{HV_i} + S_{HH_i}), \quad (9a)$$

$$V_{xi} = [(1+\kappa\kappa^*)(1+\rho\rho^*)]^{-1/2} (\rho S_{VV_i} + (1-\kappa^*\rho)S_{HV_i} - \kappa^*S_{HH_i}), \quad (9b)$$

or

$$V_{ci} = [(1+\kappa\kappa^*)(1+\rho\rho^*)]^{-1/2} (B_i + \kappa A_i) \quad (9c)$$

$$V_{xi} = [(1+\kappa\kappa^*)(1+\rho\rho^*)]^{-1/2} (-\kappa^* B_i + A_i) \quad (9d)$$

where $A_i = \rho S_{VV_i} + S_{HV_i}$, $B_i = \rho S_{HV_i} + S_{HH_i}$

To calculate the COPOL Nulls ($V_{ci}=0$) and XPOL Nulls ($V_{xi}=0$) of the i -th measurement, we assume that a common polarization transceiver antenna system is used for which the polarization ratios of the transmitting and receiving antennas become the same, i.e., $\kappa=\rho$. Hence the COPOL Nulls are

$$\rho_{cn1,2} = (1/S_{VV_i}) \left(-S_{HV_i} \pm \left(S_{HV_i}^2 - S_{HH_i} S_{VV_i} \right)^{1/2} \right) \quad (10)$$

and the XPOL Nulls are

$$\rho_{xn1,2} = (1/2a_i) [-b_i \pm (b_i^2 - 4a_i c_i)^{1/2}] \quad (11)$$

where

$$a_i = S_{HH_i}^* S_{HV_i} + S_{HV_i}^* S_{VV_i}, \quad b_i = |S_{HH_i}|^2 - |S_{VV_i}|^2, \quad c_i = -a_i^*$$

It is readily shown that the XPOL Nulls are orthonormal to each other, i.e.,

$$\rho_{xn1} \rho_{xn2}^* = -1 \text{ (condition for orthonormality).}$$

Recently, it was found in [Mieras, 1983] and in [Agrawal and Boerner, 1987] that there are two additional characteristic polarization states which produce maximum return in the orthogonally polarized channels. Thus, overall six characteristic polarization states exist: two COPOL-Nulls, two XPOL-Nulls and two XPOL-Maxs, where one of the XPOL Nulls corresponds to the COPOL Max which produces maximum return in the co-polarized channel.

For the case of the distributed fluctuating scatterers in which we use the coherency matrix formulation, the expressions of J_{11} , J_{22} as given by eqs. (14a,c) for the co-polarized and cross-polarized channels, respectively, are rather involved. So it becomes intractable to obtain an analytical expression for the XPOL Maxs for which reason we restrict our analysis to only the description of the COPOL Nulls and the XPOL Nulls which we found to be sufficient for explaining the clutter null clustering properties. These four polarization states can be represented on the Poincaré sphere in the form of a 'polarization fork' with one handle and three prongs as we have discussed in [Nespor et al., 1985]. It is shown in [Agrawal and Boerner 1987] that if we also include the XPOL-Maxs, then the 'polarization fork' is represented by one handle and five prongs as illustrated in Fig. 1, where the XPOL nulls (X_1 , X_2) are orthogonal to each other and bisect the angle made by the COPOL nulls (C_1 , C_2) at the origin of the sphere, and the XPOL Maxs are also orthogonal and represented by the antipodal points S_1 and S_2 on the Poincaré sphere where the diameter S_1S_2 is perpendicular to the diameter X_1X_2 [Agrawal and Boerner 1987].

IV.2 The Mean Characteristic Polarization State for Time-Sequential Ensemble Average Measurements

Now we consider the time-sequential ensembles of scattering matrices measured for all the N pairs of time-sequential pulses for which the voltage expressions can

be given by

$$V_C = \sum_{i=1}^N V_{Ci}, \quad V_X = \sum_{i=1}^N V_{Xi} \quad (12)$$

with the coherency matrix elements in terms of the voltages becoming

$$J_{11} = \langle V_C V_C^* \rangle, \quad J_{12} = \langle V_C V_X^* \rangle, \quad J_{22} = \langle V_X V_X^* \rangle \quad (13)$$

We assume that the random process of distributed fluctuating scatterers is ergodic [Ishimaru, 1978], then the time averages can be replaced by the time-sequential ensemble averages as shown below. Substituting eqs. (9c,d) and (12) into (13), we have

$$J_{11} = \langle V_C V_C^* \rangle = N[(1+\kappa\kappa^*)(1+\rho\rho^*)]^{-1}[\overline{|B|^2} + |\kappa|^2\overline{|A|^2} + 2\operatorname{Re}(\kappa\overline{AB^*})] \quad (14a)$$

$$J_{12} = \langle V_C V_X^* \rangle = N[(1+\kappa\kappa^*)(1+\rho\rho^*)]^{-1}[-\kappa^2\overline{AB^*} + \kappa(\overline{|A|^2} - \overline{|B|^2}) + \overline{A^*B}] \quad (14b)$$

$$J_{22} = \langle V_X V_X^* \rangle = N[(1+\kappa\kappa^*)(1+\rho\rho^*)]^{-1}[\overline{|A|^2} + |\kappa|^2\overline{|B|^2} - 2\operatorname{Re}(\kappa\overline{AB^*})] \quad (14c)$$

where $\overline{|A|^2} = \sum_{i=1}^N |A_i|^2/N$, $\overline{|B|^2} = \sum_{i=1}^N |B_i|^2/N$, $\overline{A^*B} = \sum_{i=1}^N A_i^*B_i/N$,

and the bars represent the ensemble averages of distributed fluctuating scatterers.

From experimental observations, it is found that the minimum power in the orthogonal receiving channels has non-zero values for distributed fluctuating scatterers [McCormick and Hendry, 1975; 1985]. On the other hand, for the i -th pulse measurement, it was found that the minimum power in the co-/cross-polarized channels becomes a true zero. Therefore, for distributed fluctuating scatterers, the CCPOL and XPOL Nulls could be defined by the polarization

states of the transmitter, which produce these minima in the co- and cross-polarized receiving channels, respectively. It was shown in (McCormick and Hendry, 1985) that the condition of zero correlation ($J_{12} = 0$) will be close to the minimum power in the co-/cross-polarization channels. Thus, from this condition, the mean COPOL and XPOL Nulls can be obtained. Then taking the non-zero value of J_{12} , the spread of the null polarization states about the mean values can also be calculated. Here, we point out that, in our analysis, the calculated null polarization states are given in the linear H-V basis, whereas in (McCormick and Hendry, 1985) they are derived in their preferred circular RHC-LHC basis.

Forcing $J_{12} = 0$, eq. (14b) can be written as

$$-\kappa^2 \overline{AB^*} + \kappa (\overline{|A|^2} - \overline{|B|^2}) + \overline{A^*B} = 0 \quad (15)$$

with

$$Q = \overline{AB^*}, \quad R = \overline{|A|^2} - \overline{|B|^2}$$

eq.(15) becomes

$$\kappa^2 Q - \kappa R - Q^* = 0 \quad (16)$$

$$\kappa_{1,2} = \{R \pm (R^2 + 4QQ^*)^{1/2}\} / 2Q$$

$$\kappa_{1,2} = (1/2\overline{AB^*}) \left[\overline{|A|^2} - \overline{|B|^2} \pm \sqrt{(\overline{|A|^2} - \overline{|B|^2})^2 + 4|\overline{AB^*}|^2} \right] \quad (17)$$

Substituting $\kappa_{1,2}$ in eqs.(14a,c), κ_1 (with a positive sign in eq. (17)) produces a minimum value of J_{22} and κ_2 (negative value in eq. (17)) produces a minimum value of J_{11} . Thus κ_1 and κ_2 correspond to the mean XPOL and COPOL Nulls, respectively.

A simplified solution can be obtained, if we assume that the second moment of the time-sequential ensemble-averaged scattering matrix elements of distributed scatterers is negligible [McCormick and Hendry, 1985], such that

$$\overline{AB} = \overline{A} \overline{B}, \quad \overline{|AB|^2} = \overline{|\overline{A} \overline{B}|^2} = \overline{|\overline{A}|^2} \overline{|\overline{B}|^2} \quad (18)$$

$$\text{and} \quad \overline{|A|^2} = \overline{|\overline{A}|^2}; \quad \overline{|B|^2} = \overline{|\overline{B}|^2} \quad (19)$$

This assumption is valid if we consider weak scattering from the distributed fluctuating scatterers. This assumption, simplifies the expressions of mean COPOL and XPOL Nulls. Without this assumption, the Null expressions will have fourth power of the polarization ratio, which can be solved only by numerical computations.

Substituting eq.(18,19) into eq. (17), we have

$$\kappa_1 = \frac{\overline{|A|^2}}{\overline{AB^*}} = \frac{\overline{|\overline{A}|^2}}{\overline{B^*}}, \quad \kappa_2 = -\frac{\overline{|B|^2}}{\overline{AB^*}} = -\frac{\overline{|\overline{B}|^2}}{\overline{A}} \quad (20)$$

Mean COPOL Nulls

$$\kappa_2 \overline{A} + \overline{B} = 0$$

$$\kappa_2 (\rho \overline{S_{VV}} + \overline{S_{HV}}) + \rho \overline{S_{HV}} + \overline{S_{HH}} = 0$$

where $\overline{S_{HH}}$, $\overline{S_{HV}}$ and $\overline{S_{VV}}$ are the time-sequential ensemble averages of distributed fluctuating scatterers.

For the same transmit-receive antenna, let $\kappa_1 = \rho$, then the above equation can be written as

$$\rho^2 \overline{S_{VV}} - 2\rho \overline{S_{HV}} + \overline{S_{HH}} = 0$$

$$\bar{\rho}_{\text{cnl},2} = (1/\overline{S_{VV}}) \left(-\overline{S_{HV}} \pm \left(\overline{S_{HV}}^2 - \overline{S_{HH}} \overline{S_{VV}} \right)^{1/2} \right) \quad (21)$$

where $\bar{\rho}_{\text{cnl},2}$ denote the mean COPOL Nulls.

Mean XPOL Nulls

$$\kappa_1 \overline{B^*} = \overline{A^*}$$

$$\kappa_1 (\rho^* \overline{S_{HV}^*} + \overline{S_{HH}^*}) = \rho^* \overline{S_{VV}^*} + \overline{S_{HV}^*}$$

Let $\kappa_1 = \rho$

$$|\rho|^2 \overline{S_{HV}^*} + \rho \overline{S_{HH}^*} - \rho^* \overline{S_{VV}^*} - \overline{S_{HV}^*} = 0 \quad (22)$$

Taking the conjugate of eq.(22), gives

$$|\rho|^2 \overline{S_{HV}} + \rho^* \overline{S_{HH}} - \rho \overline{S_{VV}} - \overline{S_{HV}} = 0 \quad (23)$$

From eqs. (22) and (23), we get

$$\bar{\rho}_{\text{xn1},2} = \{-\bar{b} \pm (\bar{b}^2 - 4\bar{a}\bar{c})^{1/2}\} / 2\bar{a} \quad (24)$$

where $\bar{a} = (\bar{S}_{VV} \bar{S}_{HV}^* + \bar{S}_{HH}^* \bar{S}_{HV})$; $\bar{b} = (\bar{S}_{HH})^2 - (\bar{S}_{VV})^2$; $\bar{c} = -\bar{a}^*$, and $\bar{p}_{\text{XN1},2}$ denote the mean XPOL Nulls. It can readily be shown that the mean XPOL Nulls are also orthonormal to each other, i.e., $\bar{p}_{\text{XN1}} \bar{p}_{\text{XN2}}^* = -1$.

Comparing eqs. (10), (11), (21), and (24), it is found that the mean COPOL and XPOL Nulls of the distributed fluctuating scatterer case are identical in expressions to those of the i-th measurement of the completely polarized case except that the scattering matrix parameters are replaced by their time-sequential ensemble averages in the linear polarization basis. This has also been shown using a different approach by McCormick and Hendry [1985], who in their treatments used the circular polarization state basis. Thus, the representation of the mean COPOL and XPOL Nulls becomes identical to that of the formulation for the i-th time-sequential measurement of the scattering matrix of distributed fluctuating scatterers. The values of the mean COPOL Nulls (\bar{C}_1, \bar{C}_2) and the mean XPOL Nulls (\bar{X}_1, \bar{X}_2) as calculated in eqs. (21, 24) can also be plotted on the Poincaré sphere, all found to be lying on one great circle in the form of a polarization fork as shown in Fig. 2, where the mean XPOL Nulls are orthogonal to each other, and the mean COPOL Nulls are symmetrical about the mean XPOL Null axis ($\bar{X}_1 \bar{X}_2$) and are closer to the mean XPOL Null-2 (\bar{X}_2) [Agrawal and Boerner, 1987].

IV.3 Spread of the COPOL and XPOL Nulls

In the calculation of the mean COPOL and XPOL Nulls of eq. (16), the correlation coefficient, ρ_{12} , was taken to be zero, in which case the results obtained were close to the power minima. Here we consider the non-zero value of the correlation coefficient and determine the spread of the COPOL and XPOL Nulls about the mean values calculated in eqs. (21, 24).

From eqs. (3a,b), we obtain the following

$$J_{11} = (\det(J) - |J_{12}|^2 - J_{11}^2), \text{Tr}(J) \quad (25a)$$

$$J_{22} = (\det(J) - |J_{12}|^2 - J_{22}^2), \text{Tr}(J) \quad (25b)$$

For the COPOL and XPOL Nulls, J_{11} and J_{22} are, respectively, minima. For the COPOL Null, J_{11}^2 is very small and can be neglected in eq. (25a); and for the XPOL Null, J_{22}^2 can be neglected in eq. (25b). The minima in J_{11} and J_{22} can be sensed by going to adjacent polarization states, where J_{12} is non-zero, and the J_{12} term in eq. (25a,b) equals α^2 times the minimum value [McCormick and Hendry, 1985], i.e.,

$$J_{12} = \alpha(\det(J))^{1/2} \quad (26)$$

where $\alpha = |\alpha|e^{j\psi}$ is a complex quantity and $|\alpha|=1$ corresponds to the 3dB point [McCormick and Hendry, 1985]. In eq. (14b), consider that $J_{12} \neq 0$, then we have

$$\kappa^2 Q - \kappa R - Q^* = G, \quad \text{where} \quad G = \frac{-J_{12}}{[(1+\rho\rho^*)(1+\kappa\kappa^*)]^{-1}} \quad (27)$$

Solving eq. (27), we find

$$\kappa - \kappa_0 = G / (\overline{|A|^2} + \overline{|B|^2}) \quad (28a)$$

where κ_0 is the solution of eq. (16), when $J_{12} = 0$. Expanding eq. (28a),

we have

$$(K-K_0)/(1+KK^*) = -|\alpha| e^{j\psi} \det(J)^{1/2} (\text{Tr}(J))^{-1} \quad (28b)$$

where, $\overline{|A|^2} - \overline{|B|^2} = (1+\rho\rho^*) \text{Tr}(J)$

For the monostatic case ($K=0$), we find from eqs. (5) and (28b)

$$(\rho-\rho_0)/(1+\rho\rho^*) = -(1/2)|\alpha|e^{j\psi} (1-P^2)^{1/2} \quad (28c)$$

For the 3dB point, $|\alpha|=1$, we define the spread of the null polarization states σ as

$$\sigma = |(\rho-\rho_0)/(1+\rho\rho^*)| = \frac{1}{2} (1 - P^2)^{1/2} \quad (28d)$$

where P is the degree of polarization. Thus, the spread of the COPOL and XPOL Nulls becomes

$$\sigma_{cn1,2} = \frac{1}{2} (1 - P_{cn1,2}^2)^{1/2}, \quad \sigma_{xn1,2} = \frac{1}{2} (1 - P_{xn1,2}^2)^{1/2} \quad (29)$$

where $P_{cn1,2}$ and $P_{xn1,2}$ represent the degree of polarization corresponding to the mean COPOL and XPOL Nulls, respectively.

The spread can be represented by small circles with radius σ_{cn1} and σ_{cn2} about the mean COPOL Nulls \bar{C}_1 and \bar{C}_2 , respectively, and with radius σ_{xn1} and σ_{xn2} about the mean XPOL Nulls \bar{X}_1 and \bar{X}_2 , respectively, as determined in eqs. (25, 28a) and shown in Fig. 2. It is found that the degree of polarization can be obtained from the corresponding spread of the null polarization states. This spread will disappear if the returned signal is completely polarized as it was shown for the coherent case in [Agrawal and Boerner, 1987].

IV.4 Minimum Power received at the COPOL and XPOL Nulls

The minimum power received in both the co- and cross-polarized channels at the COPOL and XPOL Nulls as compared with the total backscattered power can be estimated as follows. Let us denote the minimum power by the symbol ' χ '. McCormick and Hendry (1985) labelled this power to be the 'depth' which creates confusion in interpreting the minimum received powers in the orthogonally polarized receiving channels in terms of the interpretation of partially coherent wave properties on the polarization sphere [Deschamps and Mast, 1973].

At the COPOL Nulls, using eq. (25a) and setting $J_{12} = 0$, we get

$$\chi_{cn1,2} = \left(\frac{J_{11}}{\text{Tr}(J)} \right)_{\min} = \frac{\det(J)}{[\text{Tr}(J)]^2} \quad (30a)$$

Similarly, at the XPOL Nulls, using eq. (25b) and setting $J_{12} = 0$, we get

$$\chi_{xn1,2} = \left(\frac{J_{22}}{\text{Tr}(J)} \right)_{\min} = \frac{\det(J)}{[\text{Tr}(J)]^2} \quad (30b)$$

Hence the minimum power in the co- and cross-polarized channels can be written as

$$\chi_{cn1,2} = (1 - p_{cn1,2}^2)/4, \quad \chi_{xn1,2} = (1 - p_{xn1,2}^2)/4 \quad (31)$$

Thus by sensing the minimum powers in the orthogonally polarized receiving channels, the degree of polarization and hence the degree of correlation of the orthogonal radar channels as given by eq. (6) can be obtained.

V. TWO-DIMENSIONAL REPRESENTATION OF THE CHARACTERISTIC POLARIZATION STATES ON THE AITOFF-HAMMER EQUAL AREA PROJECTION PLOTS

We have shown in Section IV that the clustering of the COPOL and the XPOL Nulls of distributed fluctuating scatterers can be characterized by the spread on the Poincaré sphere as shown in Fig. 2. In the three-dimensional representation of the Poincaré sphere, in general, it is difficult to interpret the spread of the null-polarization states. Therefore, we need to have a two-dimensional representation of the Poincaré sphere, which can be used to represent the true spread of the null-polarization states. In many two-dimensional representations of the Poincaré sphere [Raven 1985, Huang 1985], the Aitoff-Hammer equal area projection plot of Fig. 3 is chosen because the surface area of both the Poincaré sphere and the projection are preserved. The mathematical transformation of this projection is given in Appendix. This plot is very useful in plotting the clustering behavior of the characteristic polarization states resulting from time-sequential measurements of distributed fluctuating scatterers such as that of rain, the dynamic rough sea, fluctuating terrain with and without vegetation canopy. More detailed analyses of the plots for rain scatterers are presented in [Boerner, Carnegie and Agrawal, 1986; Agrawal, 1986].

VI. POLARIMETRIC THEORY APPLIED TO A RAIN BACKSCATTER MODEL [Stapor and Pratt, 1984]

The characteristic polarization state theory derived in the previous section is applied to a rain backscatter model as described by Stapor and Pratt (1984). The objective is to extract the information about the canting angle, shape and size of distributed fluctuating raindrops modelled by dielectric oblate and prolate spheroidal hydrometeors using polarimetric rain backscatter measurements.

VI.1 Scattering Matrix for a Single Raindrop

The coherent backscattering matrix for an oblate or prolate spheroidal raindrop, as shown in Fig. 4, in the linear polarization basis is given according to Stapor and Pratt (1984) as

$$[S] = \frac{k_o^2}{4\pi\epsilon_o} \begin{bmatrix} (p_v - p_h) \cos^2 \delta \sin^2 \psi + p_h & (p_v - p_h) \cos^2 \delta \frac{\sin 2\psi}{2} \\ (p_v - p_h) \cos^2 \delta \frac{\sin 2\psi}{2} & (p_v - p_h) \cos^2 \delta \cos^2 \psi + p_h \end{bmatrix} \quad (32a)$$

where ψ is the canting angle for an oblate spheroid of Fig. 4b, and $\psi' = \psi + 90^\circ$ for a prolate spheroid of Fig. 4c. The parameter, δ , is the elevation angle, p_h and p_v are the dipole moments for the horizontal and vertical polarizations, respectively, and

$$p_h = \frac{4\pi ab^2}{3} \epsilon_o (m^2 - 1) \left[\frac{2}{I_1(1 - m^2) + m^2 + 1} \right]$$

$$p_v = \frac{4\pi ab^2}{3} \epsilon_o (m^2 - 1) \left[\frac{2}{I_1(m^2 - 1) + 1} \right]$$

m = complex index of refraction

ϵ_o = free space permittivity

$$k_o = \frac{2\pi}{\lambda}$$

$$I_1 = \frac{1}{e^2} \left(1 - \left(\frac{1}{e^2} - \frac{1}{e} \right)^{1/2} \sin^{-1} e \right)$$

$$e = \left[1 - \left(\frac{a}{b} \right)^2 \right]^{1/2}, \quad a < b \text{ for oblate raindrops}$$

$$\frac{a}{b} = 1 - 0.1\bar{a} \quad ; \quad \bar{a} = \text{equivolumetric radius}$$

We note that in this model approach motional parameters such as the direction, magnitude, shear and gradient of the velocity vector of wind and that of the descending raindrops were not considered. The analyses for both the oblate and prolate spheroids are identical except that in the analysis for the prolate spheroid, the canting angle ψ is replaced by the angle $\psi' = \psi + 90$.

VI.2 Determination of the COPOL and XPOL Nulls for a single raindrop and its graphical presentations

The XPOL Nulls for the scattering matrix of eq. (32a) can be calculated from eq. (11) as

$$\rho_{xn1} = \cot\psi, \quad \rho_{xn2} = -\tan\psi \quad (32b)$$

From eq. (32b), it is found that the XPOL Nulls are only functions of the canting angle (ψ) of the raindrop. The COPOL Nulls can also be obtained by using eq. (10) as

$$\rho_{cn1,2} = \frac{-1/2(p_v - p_h) \cos^2\delta \sin 2\psi \pm i[p_h(p_v - p_h) \cos^2\delta + p_h^2]^{1/2}}{[(p_v - p_h) \cos^2\delta \cos^2\psi + p_h]} \quad (32c)$$

In order to relate the COPOL/XPOL Nulls to the Huynen target characteristic parameters [Huynen, 1970], we diagonalize the scattering matrix of eq. (32a) in the XPOL Null basis as

$$[S_d] = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} = K \begin{bmatrix} p_v \cos^2\delta + p_h \sin^2\delta & 0 \\ 0 & p_h \end{bmatrix}; \quad K = \frac{k_o^2}{4\pi\epsilon_o} \quad (32d)$$

Thus, the COPOL Nulls in the XPOL Null basis [Agrawal and Boerner, 1987] are

$$\rho_{cn1,2} = \pm \tan(90^\circ - \gamma) e^{j(2\psi + \pi/2)} \quad (32e)$$

where

$$\tan^2 \gamma = \frac{|P_h|}{|P_v \cos^2 \delta + P_h \sin^2 \delta|}, \quad \nu = 1/4 (\theta_u - \underline{P_h}), \quad (32f)$$

and $\theta_u = \underline{P_v \cos^2 \delta + P_h \sin^2 \delta}$

For zero elevation angle ($\delta = 0^\circ$), eq. (32f) reduces to

$$\tan^2 \gamma = |P_h/P_v|, \quad \nu = 1/4 (\angle P_v - \angle P_h) \quad (32g)$$

For 90° elevation angle ($\delta = 90^\circ$), we have

$$\tan^2 \gamma = 1, \quad \gamma = 45^\circ, \quad \nu = 0^\circ, \quad \rho_{cn1,2} = \pm i \quad (32h)$$

Comparing eqs. (32g,h), we find that when $\delta = 90^\circ$, the COPOL Nulls lie on the LHC and RHC polarization states. This is because, for this case, the oblate/prolate spheroids look like spheres. On the other hand, for zero elevation angle, $\delta = 0^\circ$, the COPOL Nulls move away from the circular polarization state location (poles), where the shift will depend on the amplitude ratio of the horizontal and vertical dipole moments. Here we consider the following cases of a spheroid: (i) when the spheroids are degenerate to spheres ($a=b$), then the COPOL Nulls will lie at the circular polarization states on the Poincaré sphere because $P_h=P_v$, (ii) when the spheroidal parameter, a , tends to zero, then the oblate spheroid behaves like a horizontal dipole and the prolate spheroid behaves like a vertical dipole. In these cases, the characteristic polarization state corresponding to the maximum power return (point x_1 on the Poincaré sphere) of the horizontal dipole is the horizontal polarization, and that corresponding to the vertical dipole is the vertical polarization. The corresponding COPOL Nulls are located at vertical polarization for the horizontal dipole, and at horizontal polarization for the vertical dipole, the detailed description is given in [Agrawal, 1986].

The polarization fork and corresponding co-/cross-power spectral plots (Agrawal & Boerner, 1987) for oblate spheroids with different axis ratios (a/b), and canting angles (ψ) are shown in Figs. 5 to 7. The polarization forks for prolate spheroids are collected in Fig. 8. Here we would like to point out again that in the case of prolate spheroids, the canting angle is replaced by $\psi + 90^\circ$ where ψ corresponds to oblate spheroids. From Figs. 5 to 7 for the oblate spheroids, it is found that if the canting angle of the raindrop is zero, then the "great circle of the null/max polarization states" is described by the main circle $\phi=0^\circ$. If the canting angle is non zero ($\psi \neq 0^\circ$), the great circle moves in the clockwise direction about the z-axis for increasing positive values of ψ , and in anti-clockwise direction for increasing negative values of ψ . The XPOL Nulls lie on the equatorial plane and represent the rotation of the great circle around the z-axis. The COPOL Nulls drift away from the circular polarization states with the decreasing values of the axis ratios, and approach the XPOL Null 2. The power spectral plots clearly show the maximum and minimum power returns in the co-/cross- polarized channels.

Comparing the results of oblate spheroids as shown in Figs. 5 to 7 with the results of the prolate spheroids of Fig. 8, we find that the polarization forks in both the cases are identical except that the great circle, in addition, rotates clockwise by 180° in the case of the prolate spheroids. We need to point out, however, that the Stapor/Pratt model does not contain any description of prevailing wind effects such as direction, velocity, shear, gradient, etc. For example, the case for which the canting angle relates to the azimuthal angle on the polarization sphere, corresponds to a two-dimensional wind velocity gradient confined to a plane transverse to the observation direction (Agrawal, 1986). On the other hand, the cases in which

the wind velocity gradient occurs in any general direction cannot be accommodated in the current Stapor/Pratt model, because the XPOL Nulls then will move not along the equatorial main circle but on another non-equatorial main circle depending upon the direction of the wind velocity gradient.

VI.3 Determination of mean CCOPOL and mean XPOL Nulls for a volume of fluctuating hydrometeoric scatterers

For distributed fluctuating hydrometeoric scatterers, the time-sequential ensemble-averaged scattering matrix elements of eq. (32a) must be sought, where we assume that the distribution of the canting angle is Gaussian (with mean canting angle ($\bar{\psi}$) and variance (σ)) and independent of the hydrometeoric size [Metcalf and Ussailis, 1984]. The time-sequential ensemble averages of eq. (32a) can then be expressed as

$$\overline{S_{HH}} = K [1/2(\bar{p}_V - \bar{p}_H) \cos^2 \delta (1 - \cos^2 \bar{\psi} \beta_\psi) + \bar{p}_H] \quad (33a)$$

$$\overline{S_{HV}} = K [1/2(\bar{p}_V - \bar{p}_H) \cos^2 \delta \sin^2 \bar{\psi} \beta_\psi] \quad (33b)$$

$$\overline{S_{VV}} = K [1/2(\bar{p}_V - \bar{p}_H) \cos^2 \delta (1 + \cos^2 \bar{\psi} \beta_\psi) + \bar{p}_H] \quad (33c)$$

where $K = k_0^2 / 4\pi\epsilon_0$, and the quantities \bar{p}_H and \bar{p}_V are the time-sequential ensemble averages of the dipole moments. The parameter β_ψ is sometimes identified as the "degree of orientation" of the scattering medium [Metcalf and Ussailis, 1984], and is defined by

$$\beta_\psi = [1/(2\pi\sigma_\psi^2)]^{1/2} \int_{-\pi/2}^{\pi/2} \cos 2(\psi - \bar{\psi}) \exp\{-(\psi - \bar{\psi})^2 / 2\sigma_\psi^2\} d(\psi - \bar{\psi}) \quad (34)$$

where $\bar{\psi}$ is the mean canting angle, and σ is the variance with a distribution between $-\pi/2$ and $\pi/2$. Metcalf and Ussailis (1984) showed that since $\cos 2(\psi - \bar{\psi})$ is cyclic over each increment $\Delta(\psi - \bar{\psi}) = \pi$, the integral in eq. (34) can be replaced by an integral from $-\infty$ to $+\infty$, so that

$$\beta_{\psi} = \exp(-2\sigma_{\psi}^2) \quad (35)$$

Using eqs. (33a-c), the mean COPOL and mean XPOL Nulls from eqs. (21, 24) are calculated as

Mean XPOL Nulls:

$$\bar{\rho}_{xn1} = \cot \bar{\psi}, \quad \bar{\rho}_{xn2} = -\tan \bar{\psi} \quad (36)$$

Mean COPOL Nulls:

$$\bar{\rho}_{cn1,2} = \frac{-\frac{1}{2}(\bar{p}_v - \bar{p}_h) \cos^2 \delta \sin 2\bar{\psi} \beta_{\psi} \pm [1/4(\bar{p}_v - \bar{p}_h)^2 \cos^4 \delta (\beta_{\psi}^2 - 1) - (\bar{p}_v - \bar{p}_h) \bar{p}_h \cos^2 \delta - \bar{p}_h^2]^{1/2}}{[1/2(\bar{p}_v - \bar{p}_h) \cos^2 \delta (1 + \cos 2\bar{\psi} \beta_{\psi}) + \bar{p}_h]} \quad (37)$$

For zero elevation angle ($\delta=0^\circ$), we obtain

$$\bar{\rho}_{cn1,2} = \frac{-1/2(\bar{p}_v - \bar{p}_h) \sin 2\bar{\psi} \beta_{\psi} \pm [1/4(\bar{p}_v - \bar{p}_h)^2 (\beta_{\psi}^2 - 1) - \bar{p}_v \bar{p}_h]^{1/2}}{[1/2(\bar{p}_v - \bar{p}_h)(1 + \cos 2\bar{\psi} \beta_{\psi}) + \bar{p}_h]} \quad (38)$$

whereas for 90° elevation angle ($\delta=90^\circ$)

$$\bar{\rho}_{cn1,2} = \pm i \quad (39)$$

In order to relate the CCPOL Nulls to the Huynen target parameters, we find the averaged diagonalized scattering matrix, similar to eq. (32d) as,

$$(\bar{S}_d) = \begin{bmatrix} \bar{\lambda}_1 & 0 \\ 0 & \bar{\lambda}_2 \end{bmatrix} = K \begin{bmatrix} \frac{\cos^2 \delta}{2} (\bar{P}_v - \bar{P}_k) (1 + \beta_\psi) + \bar{P}_k & 0 \\ 0 & \frac{\cos^2 \delta}{2} (\bar{P}_v - \bar{P}_k) (1 - \beta_\psi) + \bar{P}_k \end{bmatrix} \quad (40)$$

Now, the COPOL Nulls in the XPOL Null basis can be written as

$$\bar{\zeta}_{cn1,2} = \pm \tan(90^\circ - \bar{\gamma}) e^{i(2\bar{v} + \pi/2)} \quad (41)$$

where

$$\tan^2 \bar{\gamma} = \left| \frac{\frac{\cos^2 \delta}{2} (\bar{P}_v - \bar{P}_k) (1 - \beta_\psi) + \bar{P}_k}{\frac{\cos^2 \delta}{2} (\bar{P}_v - \bar{P}_k) (1 + \beta_\psi) + \bar{P}_k} \right| \quad (42a)$$

$$\bar{v} = 1/4 (\angle \bar{\lambda}_1 - \angle \bar{\lambda}_2) \quad (42b)$$

For zero elevation angle ($\delta = 0^\circ$)

$$\tan^2 \bar{\gamma} = \left| \frac{-\beta_\psi (\bar{P}_v - \bar{P}_k) + (\bar{P}_v - \bar{P}_k)}{\beta_\psi (\bar{P}_v - \bar{P}_k) + (\bar{P}_v - \bar{P}_k)} \right| \quad (43a)$$

$$\bar{v} = 1/4 (\angle(\bar{P}_v + \bar{P}_k) + \beta_\psi (\bar{P}_v - \bar{P}_k) - (\angle(\bar{P}_v + \bar{P}_k) - \beta_\psi (\bar{P}_v - \bar{P}_k))) \quad (43b)$$

For 90° elevation angle ($\delta = 90^\circ$),

$$\tan^2 \bar{\gamma} = 1, \bar{\gamma} = 45^\circ, \bar{v} = 0^\circ, \bar{\zeta}_{cn1,2} = i \quad (44)$$

From eq. (36), it is observed that the mean canting angle ($\bar{\psi}$) can be obtained from the mean XPOL Nulls which are represented by the longitude on the

Poincaré sphere [Agrawal, 1986] for the case in which the wind shear is considered to be confined to a plane normal to the observation direction. From the expression of the mean COPOL Nulls, it is shown that for vertical elevation angle, the mean COPOL Nulls are located at the circular polarization states as they should be, because at this aspect the descending raindrops assume spherical shape about the specular point. For zero elevation angle if the raindrop particles are non-spherical i.e., oblate/prolate spheroids, the mean COPOL Nulls are located away from the circular polarization state points on the great circle of the Poincaré sphere, where the closeness of the COPOL Nulls to the circular polarization states will depend on the ratio of the amplitude of the time-sequential ensemble-averaged values of \bar{p}_h and \bar{p}_v . For a horizontal dipole cloud, the mean COPOL Nulls should lie close to the mean XPOL Null-2. Thus, we conclude that the location of the COPOL Nulls on the polarization sphere provides information about the shape of the raindrop particles [Poelman and Guy, 1985]. Here, we reemphasize that it was precisely this observation which motivated Kennaugh already in 1948 to initiate his investigations of polarimetric radar theory and phenomenology as summarized in detail in [Kennaugh, 1949-1954].

VII CONCLUSIONS

The mean COPOL and the mean XPOL Nulls for distributed fluctuating scatterers are derived by using a simplified statistical approach which makes use of the coherency density matrix formulation, but will require further in depth analytical model development and the introduction of properly defined distribution functions as is pointed out in [Kostinski, James, and Boerner, 1988]. Using our simplified rain backscatter model, it has been shown that the expressions of the mean COPOL and XPOL Nulls of distributed fluctuating scatterers assume a similar form as those of the i-th time-sequential

measurement of the distributed scatterers except that the scattering matrix elements were replaced by their time-sequential ensemble averages as given in eqs. (10, 11, 21, 24). The spread of the COPOL and XPOL Nulls were calculated in terms of the degree of the polarization state of the backscattered signal and so were the expressions of the received power at these null polarization states. Similar results were obtained by [McCormick and Hendry, 1985]. Because the range of the degree of polarization is confined to $0 \leq P \leq 1$, the ranges of the spread and the minimum power received become $0 \leq \sigma \leq 1/2$ and $0 \leq X \leq 1/4$. This shows that in the coherent case (with degree of polarization, $P=1$), the spread disappears and the power received at these null polarization states becomes zero approaching the coherent case. A two-dimensional Aitoff-Hammer equal area projection plot was introduced in order to analyse the clustering properties of the COPOL and XPOL Nulls determined from time-sequential measurement of the scattering matrices of distributed fluctuating scatterers such as rain.

The mean clutter null theory was applied to a backscatter rain model as developed by Stapor and Pratt (1984). It was determined that the mean XPOL Nulls may provide a direct measure of the mean canting angle, on the other hand the mean COPOL Nulls may provide a means of determining the shape of the hydrometeors for a given aspect and frequency. For vertical elevation of the radar beam, it was shown that the mean COPOL Nulls are located at the circular polarization states for which the raindrops assume, in general, spherical shape in the backscatter direction as viewed from the polarimetric radar location.

Both the basic distributed fluctuating scatterer model and the rain backscatter model, derived in Sections III and IV of this study, were assessed partly

on their validity using the polarimetric data collected with a coherent dual-polarization pulsed X-band radar [Agrawal, 1986]. The obtained results are quite satisfactory and encouraging in that our approach, making use of both the polarimetric clutter null and power spectral plot descriptions, provides a useful tool for radar meteorology as well as for the efficient discrimination of slowly moving compact targets in fluctuating hydrometeorological clutter [Boerner, Carnegie and Agrawal, 1986].

VIII ACKNOWLEDGEMENTS

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APPENDIX
THE MATHEMATICAL TRANSFORMATION OF THE AITOFF-HAMMER
EQUAL AREA PROJECTION PLOTS
[Huang, 1985; Raven, 1985]

The mathematical transformation of this projection process involves a transformation from a spherical coordinate system to a rectangular coordinate system. Systematically, the projection process consists of two steps: first, generating three parameters used in the transformation; and second, making the transformation.

Input Coordinates: (spherical coordinate)

Latitude: ϕ , ϕ_0 (the coordinate of the centre)

Longitude: λ , λ_0 (the coordinate of the centre)

Output Coordinates: (rectangular coordinate)

X coordinate: X (longitude line)

Y coordinate: Y (latitude line)

Intermediate Parameter Expressions: A_1, A_2, A_3

$$A_1 = \cos^{-1} \left(\cos(\phi/2) \cos(\lambda/2) + \cos(\phi_0/2) \cos(\lambda_0/2) \right) \quad (A.1)$$

$$A_2 = \sqrt{2} \sin(A_1/2) \quad (A.2)$$

$$A_3 = \sin^{-1} (\sin(\lambda - \lambda_0) / \sin(A_1)) \quad (A.3)$$

Transformation Operation:

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} 2A_1 \cos(A_2) \\ A_2 \sin(A_3) \end{pmatrix} \quad (A.4)$$

The computer program using these equations is developed in [Huang, 1985].

FIGURE CAPTIONS

- Fig. 1: Representation of the characteristic polarization states for a single scatterer on the Poincaré sphere (XPOL Nulls: X_1, X_2 ; COPOL Nulls: C_1, C_2 ; target characteristic angle: γ)
- Fig. 2: Representation of the characteristic polarization states for a time-sequential ensemble of measurements of fluctuating distributed scatterers on the Poincaré sphere (Mean XPOL Nulls: \bar{X}_1, \bar{X}_2 ; COPOL Nulls: \bar{C}_1, \bar{C}_2 ; target characteristic angle: $\bar{\gamma}$; spread of XPOL Nulls: $\sigma_{xn1}, \sigma_{xn2}$; spread of COPOL Nulls: $\sigma_{cn1}, \sigma_{cn2}$)
- Fig. 3: The Aitoff-Hammer equal area projection plot of the Poincaré sphere
- Fig. 4: a) Geometry of a dielectric raindrop for the Stapor/Pratt model (borrowed from Stapor and Pratt, 1984)
b) Shape of oblate spheroid
c) Shape of prolate spheroid
- Fig. 5: The polarization-fork and the co-/cross-polarization spectra of a single dielectric oblate raindrop for the cases (a) the axial ratio $a/b = 0.9$ and the canting angle $\psi = 2.5^\circ$, and (b) the axial ratio $a/b = 0.9$ and the canting angle $\psi = 20^\circ$ (ϕ and τ are the tilt and the ellipticity angles, respectively, of a polarization ellipse as defined in [Agrawal and Boerner, 1986]; $|V_c|^2$ and $|V_x|^2$ are the co-polarized and the cross-polarized power returns, respectively)
- Fig. 6: The polarization-fork and the co-/cross-polarization spectra of a single dielectric oblate raindrop for the cases (a) the axial ratio $a/b = 0.5$ and the canting angle $\psi = 5^\circ$, and (b) the axial ratio $a/b = 0.5$ and the canting angle $\psi = 30^\circ$
- Fig. 7: The polarization-fork and the co-/cross-polarization spectra of a single dielectric oblate raindrop for the cases (a) the axial ratio $a/b = 0.3$ and the canting angle $\psi = -10^\circ$, and (b) the axial ratio $a/b = 0.3$ and the canting angle $\psi = -50^\circ$

Fig. 8: The polarization forks of prolate spheroids for the cases:

a) $a/b = 0.9$, $\psi = 92.5^\circ$

b) $a/b = 0.9$, $\psi = 110^\circ$

c) $a/b = 0.5$, $\psi = 95^\circ$

d) $a/b = 0.5$, $\psi = 120^\circ$

e) $a/b = 0.3$, $\psi = 80^\circ$

f) $a/b = 0.3$, $\psi = 40^\circ$

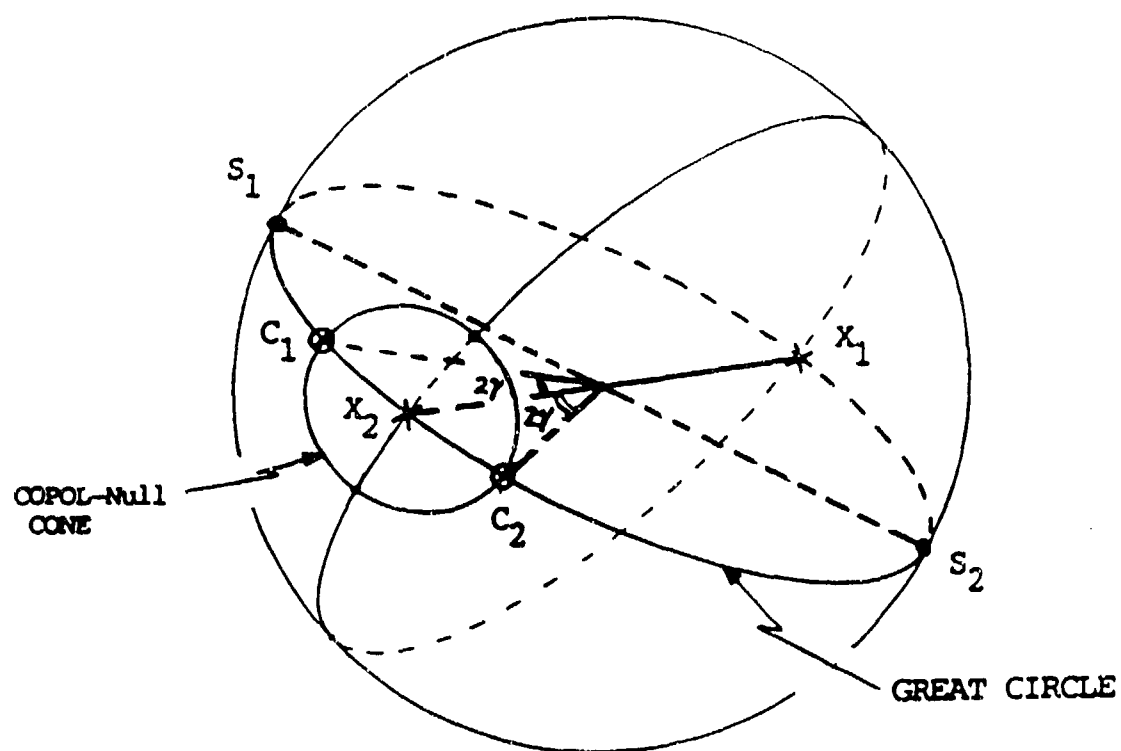


Fig. 1: Representation of the characteristic polarization states for a single scatterer on the Poincaré sphere (XPOL Nulls: X_1 , X_2 ; COPOL Nulls: C_1 , C_2 ; target characteristic angle: γ)

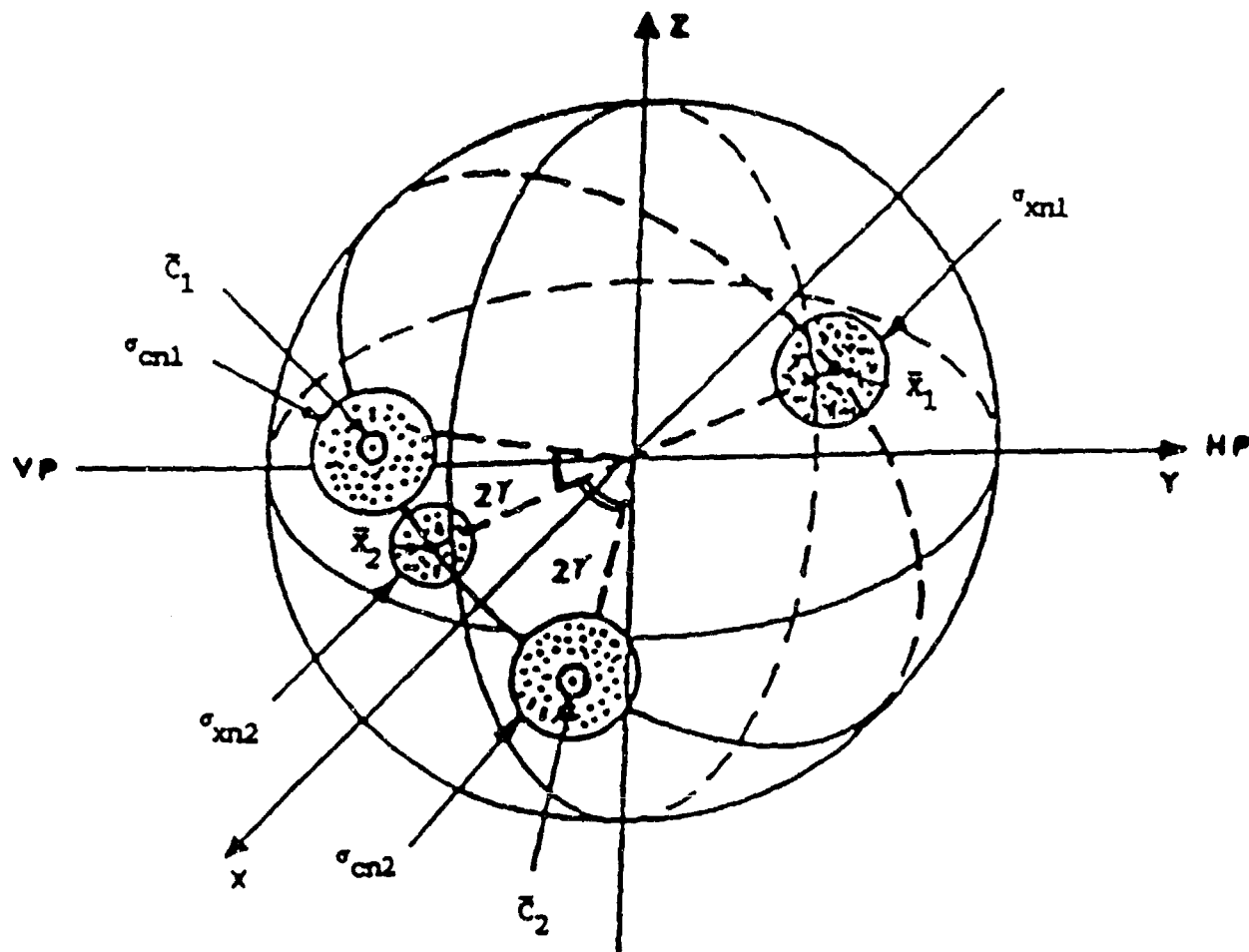


Fig. 2: Representation of the characteristic polarization states for a time-sequential ensemble of measurements of fluctuating distributed scatterers on the Poincaré sphere (Mean XPOL Nulls: \bar{x}_1, \bar{x}_2 ; COPOL Nulls: \bar{c}_1, \bar{c}_2 ; target characteristic angle: $\bar{\gamma}$; spread of XPOL Nulls: $\sigma_{xn1}, \sigma_{xn2}$; spread of COPOL Nulls: $\sigma_{cn1}, \sigma_{cn2}$)

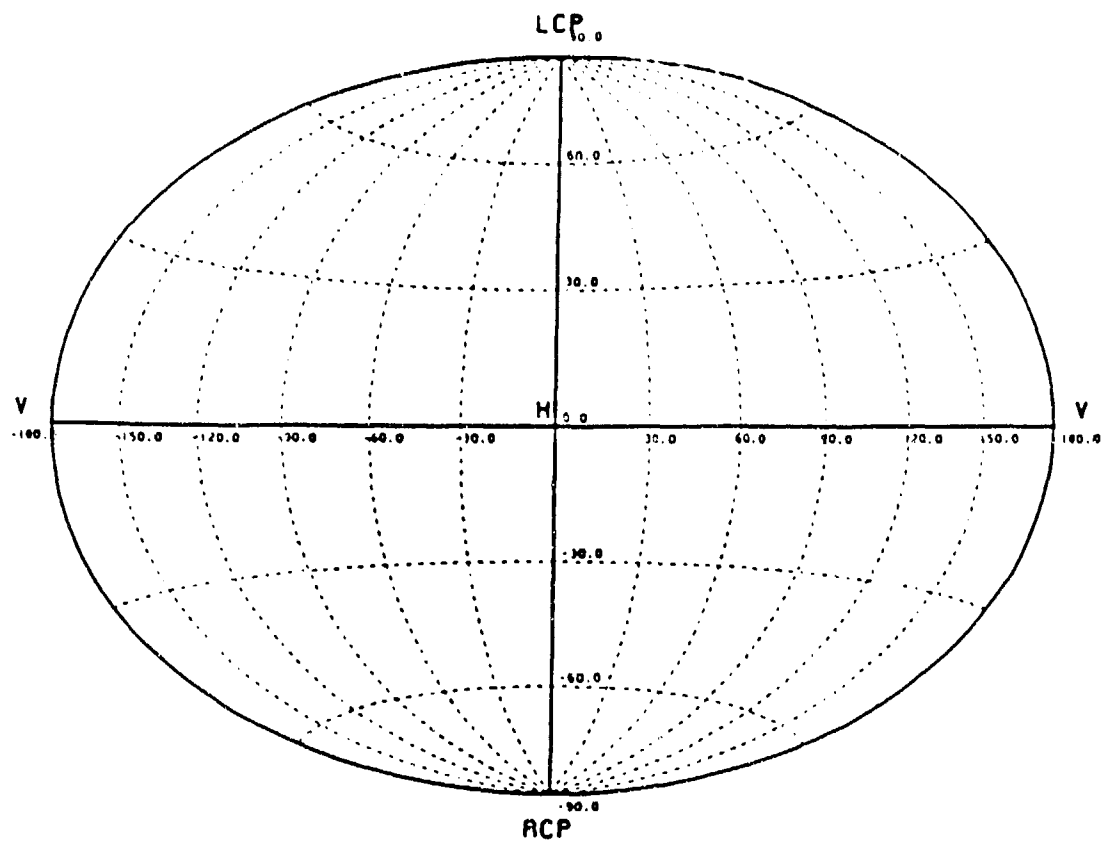


Fig. 3: The Aitoff-Hammer equal area projection plot of the Poincaré sphere

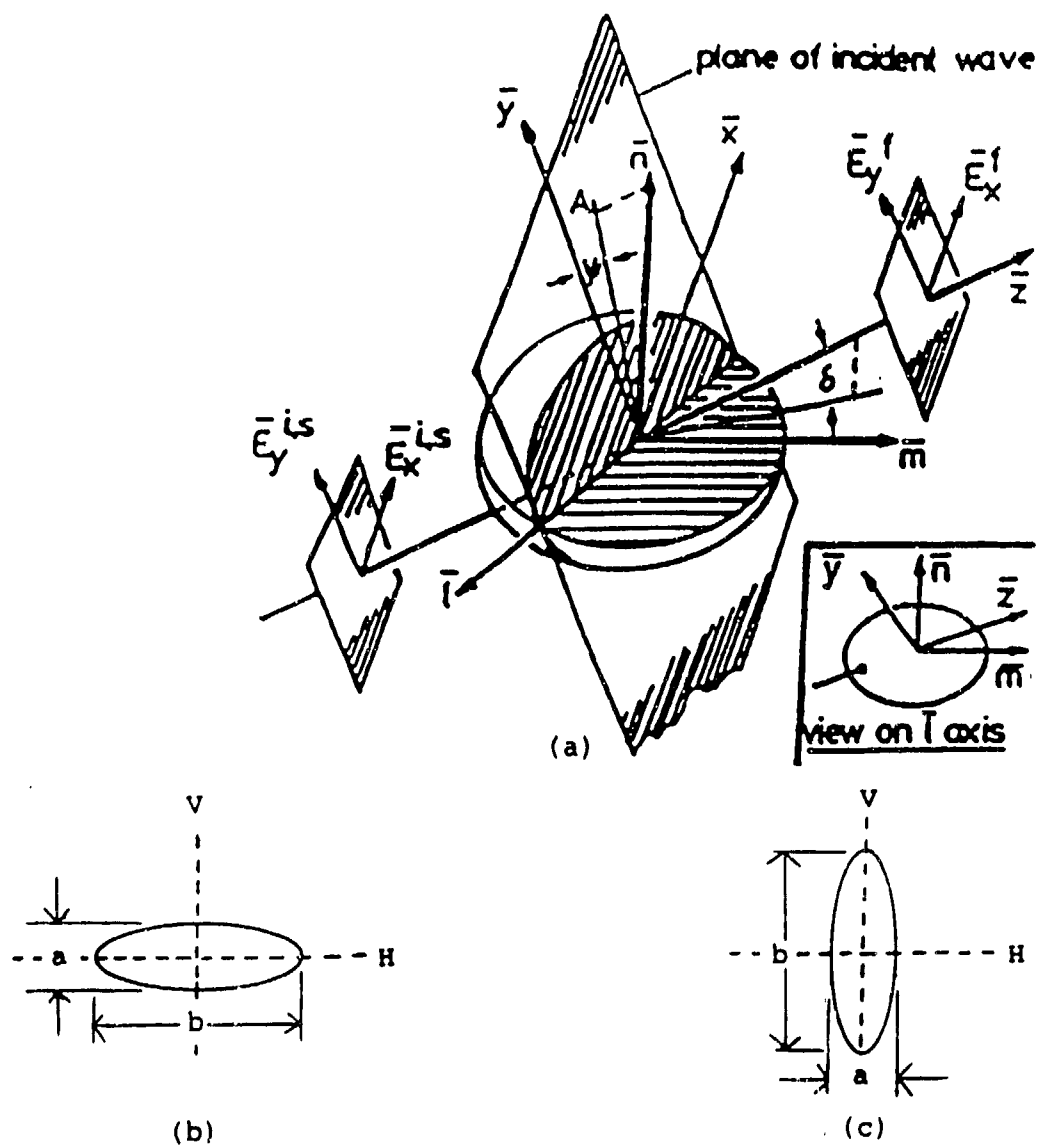
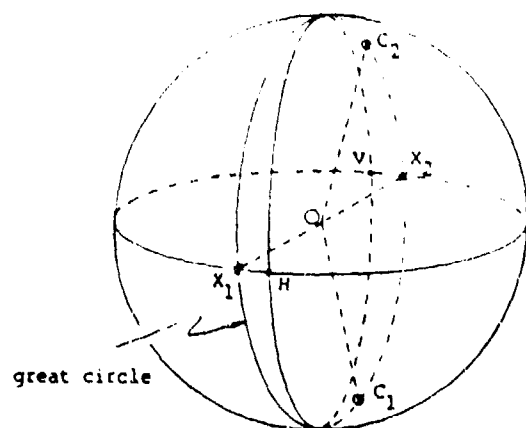
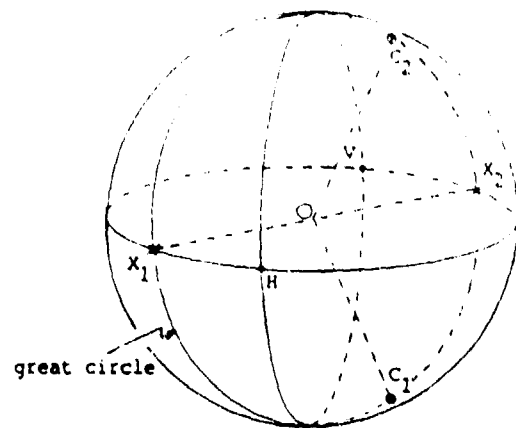


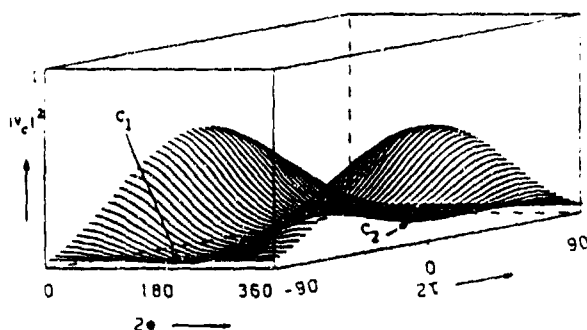
Fig. 4: (a) Geometry of a dielectric raindrop for the Stapor/Pratt model (borrowed from Stapor and Pratt, 1984) (b) Shape of oblate spheroid (c) Shape of prolate spheroid



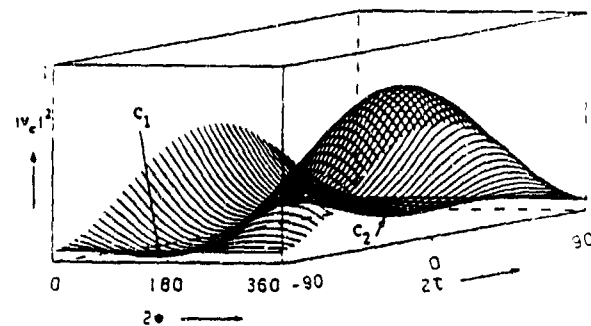
Polarization-fork



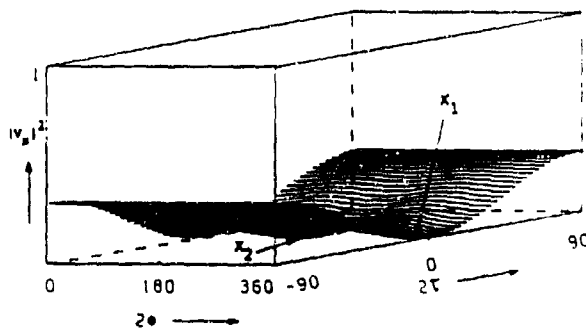
Polarization-fork



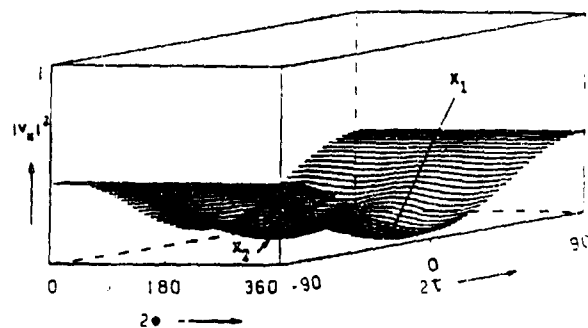
Co-polarization power spectrum



Co-polarization power spectrum



Cross-polarization power spectrum

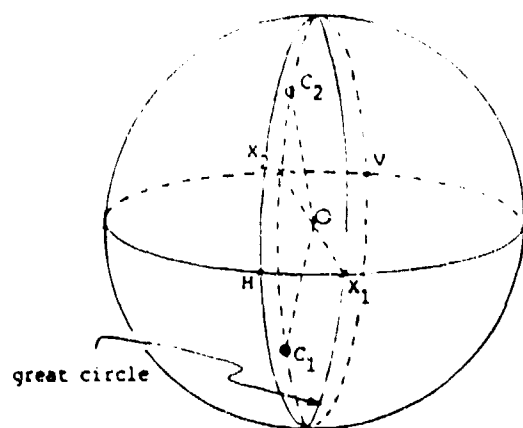


Cross-polarization power spectrum

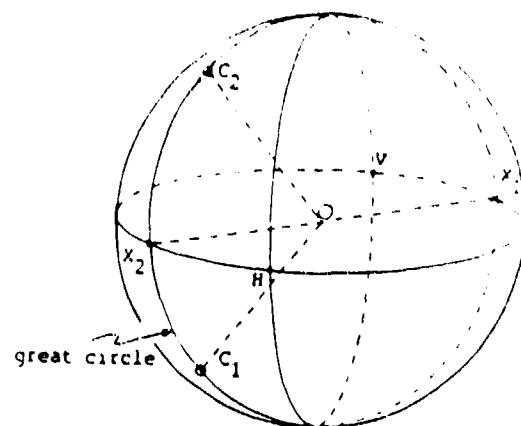
(a)

(b)

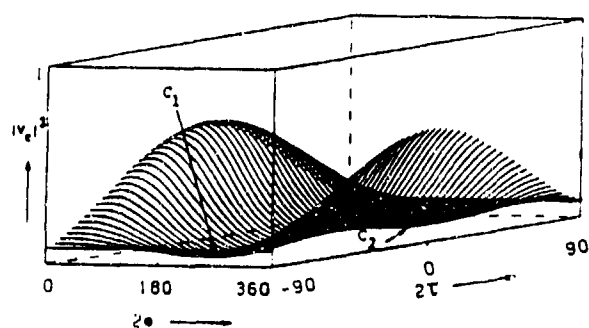
Fig. 6: The polarization-fork and the co-/cross-polarization spectra of a single dielectric oblate raindrop for the cases (a) the axial ratio $a/b = 0.5$ and the canting angle $\psi = 5^\circ$, and (b) the axial ratio $a/b = 0.5$ and the canting angle $\psi = 30^\circ$



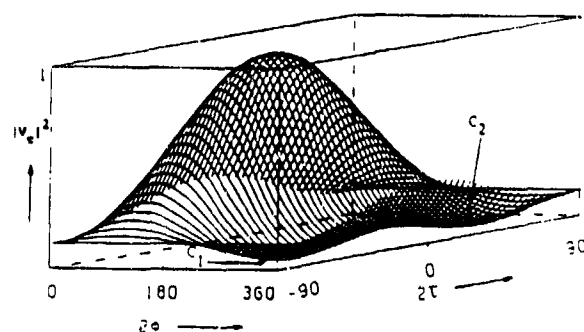
Polarization-fork



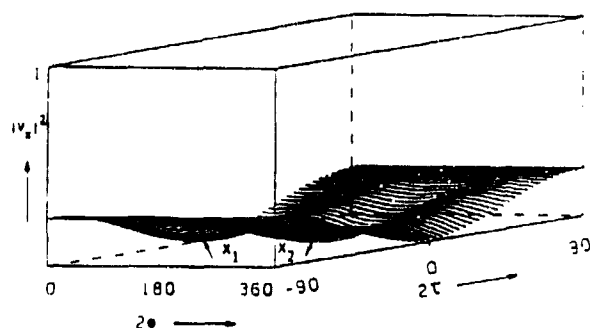
Polarization-fork



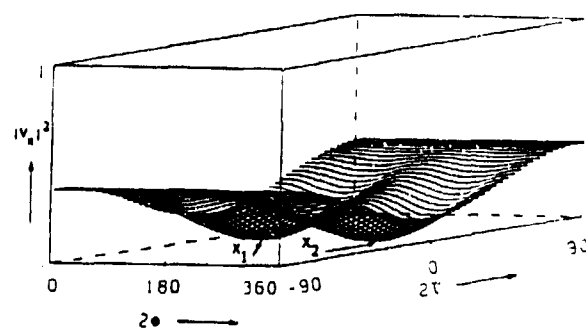
Co-polarization power spectrum



Co-polarization power spectrum



Cross-polarization power spectrum



Cross-polarization power spectrum

(a)

(b)

Fig. 7: The polarization-fork and the co-/cross-polarization spectra of a single dielectric oblate raindrop for the cases (a) the axial ratio $a/b = 0.3$ and the canting angle $\psi = -10^\circ$, and (b) the axial ratio $a/b = 0.3$ and the canting angle $\psi = -50^\circ$

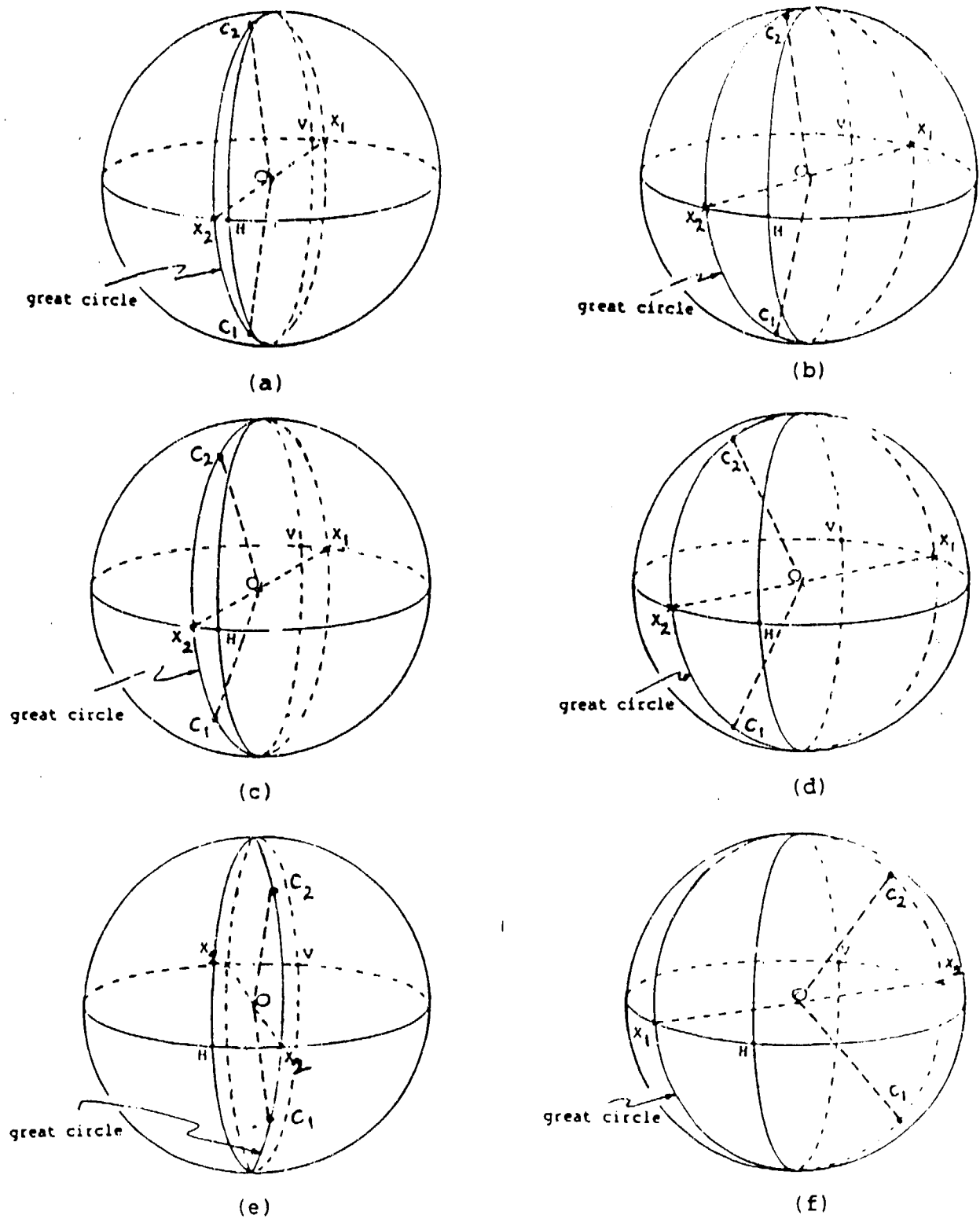


Fig. 8: The polarization forks of prolate spheroids for the cases (a) $a/b = 0.9$, $\psi = 92.5^\circ$ (b) $a/b = 0.9$, $\psi = 110^\circ$ (c) $a/b = 0.5$, $\psi = 95^\circ$ (d) $a/b = 0.5$, $\psi = 120^\circ$ (e) $a/b = 0.3$, $\psi = 80^\circ$, and (f) $a/b = 0.3$, $\psi = 40^\circ$

A Re-Examination of Radar Terrain Backscattering at Nadir

HYO J. EOM, MEMBER, IEEE, AND WOLFGANG-M. BOERNER, FELLOW, IEEE

Abstract—The theoretical behavior of nadir specular and diffuse radar backscattering from rough terrain is re-examined. Terrain is modeled as a random rough surface in the Kirchhoff approximation. The relative significance of specular (coherent) and diffuse (noncoherent) radar backscatter is compared in terms of the antenna system parameters (beamwidth, height, and frequency) and rough surface statistics. It has been found that in case of a high-altitude (space or airborne) radar, the ratio between coherent and noncoherent terrain backscatter is independent of its altitude of the radar platform. A possible explanation is suggested for the anomalous radar backscatter observed in the Skylab S-193 altimeter experiment.

I. INTRODUCTION

THE BEHAVIOR of terrain radar backscatter at normal incidence is an important subject to a radar system designer. Radar backscatter at nadir is, in general, a specular-dominant phenomenon when terrain is fairly smooth, while it tends to be diffuse-dominant as terrain becomes rougher.

In order to explain the diffuse/specular behavior of radar return, random rough surface scatter models have been proposed and used [1]–[5]. Recently, Moore [6] has proposed a simple empirical-type formula that estimates a ratio of specular to diffuse radar backscatter in terms of surface roughness parameters.

The purpose of this paper is to study the relative importance of nadir-specular/diffuse radar backscatter using available theoretical surface scatter models developed by Fung and Eom [4], [5]. It should be mentioned that the scatter models in [4], [5] are developed with the random rough surface scattering theory in the Kirchhoff approximation.

In the next section, we shall 1) derive the ratio of specular to diffuse backscatter from the Kirchhoff random rough surface, and examine its behavior versus roughness parameters; and 2) give a possible explanation for an anomalously strong specular return from terrain measured in the skylab experiment [7].

II. COHERENT AND NONCOHERENT SCATTERING COEFFICIENT

The coherent (specular) and noncoherent (diffuse) scattering coefficients (σ_C^0 and σ_n^0) of a random rough Kirch-

hoff surface have been derived by Fung and Eom [4] and Ulaby et al. [5]. It is assumed that the random surface height is Gaussian distributed, and the correlation of the surface height is also Gaussian. They are given, at nadir, as

$$\sigma_C^0 = |R|^2 \exp(-k_0) \left/ \left[\frac{1}{(k^2 h^2 \beta_0^2)} + \frac{\beta_0^4}{4} \right] \right. \quad (1)$$

$$\sigma_n^0 = 2|R|^2 (kl)^2 \exp(-k_0) \sum_{m=1}^{\infty} \frac{(k_0)^m}{(m!m)} \quad (2)$$

where

- R is the Fresnel reflection coefficient at nadir;
- k $2\pi/\lambda$: λ is the incidence wavelength;
- h is the radar altitude;
- β_0 is the one-way one-sided field beamwidth ($\approx 0.85 \beta$, β is a one-way two-sided power beamwidth);
- k_0 $4k^2 \sigma^2$ (σ : standard deviation of surface height); and
- l is the rough surface height correlation length.

Due to the Kirchhoff approximation used to derive (1) and (2), the range of applicability of σ_C^0 and σ_n^0 is limited. It is given by the following two conditions [5]

$$kl > 10 \quad (3a)$$

$$l^2 > 2.76\sigma\lambda. \quad (3b)$$

Note that the conditions (3) stipulate that the scale of horizontal roughness structure (l) be much larger than the vertical roughness structure (σ).

Taking the ratio σ_n^0/σ_C^0 , we get

$$\sigma_n^0/\sigma_C^0 = 2(kl)^2 (1/k^2 h^2 \beta_0^2 + \beta_0^2/4) \sum_{m=1}^{\infty} \frac{(k_0)^m}{m!m}. \quad (4)$$

Equation (4) indicates that σ_n^0/σ_C^0 depends upon the system parameters β_0 , λ , and h as well as rough surface statistics σ and l . Hence, in order to study the effects of σ and l on σ_n^0/σ_C^0 , we need *a priori* information on the values of β_0 , λ , and h . In what follows, we shall separately consider two different cases: (1) radar at a low-altitude platform, i.e., truck-mounted; and (2) radar at a high-altitude platform, i.e., space-borne radar.

1) First, take the L-band truck-mounted scatterometer [8] used for radar clutter measurements of agricultural scenes. Its system parameters are $h = 10$ m, $\beta_0 = 0.172$ rad, and $\lambda = 20$ cm. Using these parameters, we plot σ_n^0/σ_C^0 versus $k\sigma$ in Fig. 1. σ and l values used in Fig. 1 are typical for agricultural bare ground [5]. It is seen that un-

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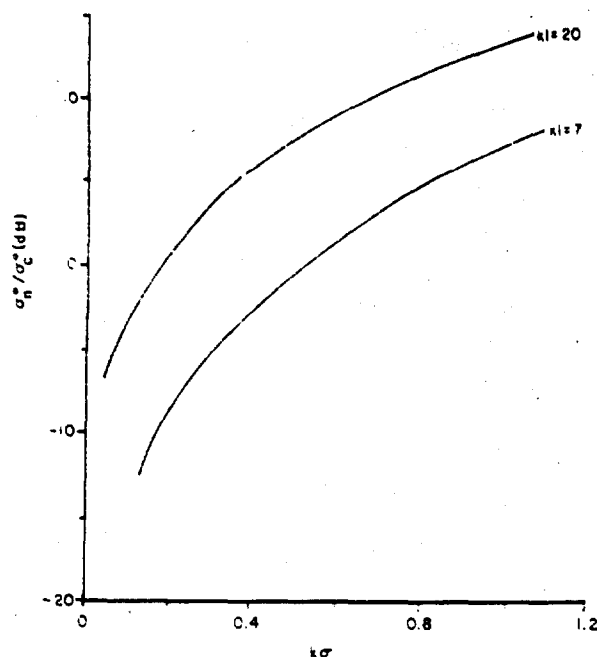


Fig. 1. The theoretical behavior of σ_n^0/σ_c^0 versus $k\sigma$. l and σ are the surface height correlation length and the surface height standard deviation, respectively.

less σ and l are extremely small, i.e., both $k\sigma < 0.5$ and $kl < 7$, diffuse backscattering is dominant over the specular one.

2) In the case of high-altitude radar ($h > 400$ m), it should be noted that the far-zone criteria, $h \gg D^2/\lambda$ ($D = 0.5 \lambda/\beta_0$) can be easily satisfied. Consequently, (4) simplifies to

$$\sigma_n^0/\sigma_c^0 = 0.5(kl)^2\beta_0^2 \sum_{m=1}^{\infty} (k\sigma)^m/(m!m). \quad (5)$$

Note that the ratio σ_n^0/σ_c^0 is now independent of the radar altitude h . Also note that an increase in either σ or l may result in an increase in σ_n^0/σ_c^0 . This means that diffuse radar backscatter σ_n^0 is expected to increase either by increasing the vertical roughness scale (σ) or the horizontal roughness scale (l) of the terrain. This σ_n^0 -increase due to l -increase may seem peculiar at first glance. But this is not so since an increase in l results in steeper trends of angular σ_n^0 , and subsequently in larger σ_n^0 at nadir.

It is also interesting to note that in the case of a perfect planar terrain ($\sigma \rightarrow 0$ and $l \rightarrow 0$), σ_n^0/σ_c^0 is seen to approach zero.

When kh is large, the effective beamwidth is reduced. This occurs because the effective beamwidth involves the combined effects of the scattering beamwidth (based on shape and steepness of the σ'' curve) and the actual antenna beamwidth. When the effective beamwidth is small enough, either because of the antenna or the scattering, the condition for dominance by specular backscatter in [6] is satisfied. This occurs because the effective area involved in random scattering is reduced, thereby reducing the number of "small scatterers" contributing to the ran-

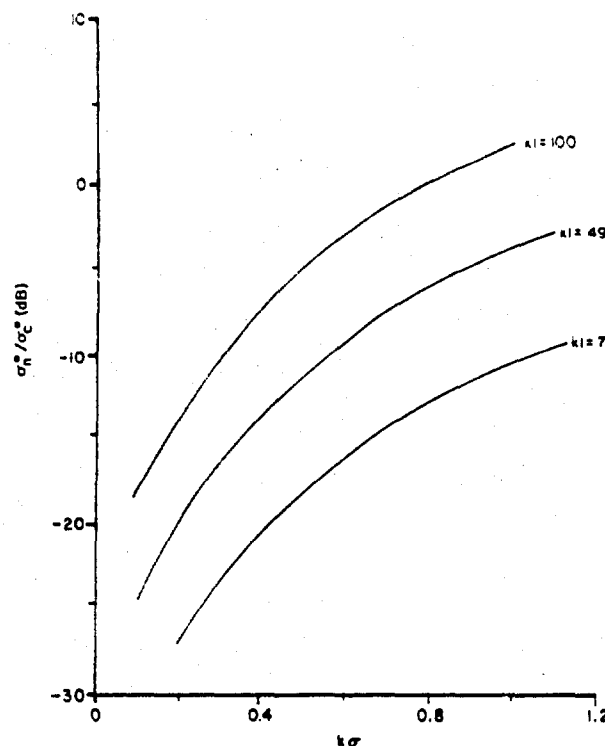


Fig. 2. Theoretical behavior of σ_n^0/σ_c^0 versus $k\sigma$. l and σ are the surface height correlation length and the surface height standard deviation, respectively.

domly phased return without reducing the specular component.

In order to study the high-altitude radar backscatter behavior versus the roughness $k\sigma$, we select system parameters of the Skylab S-193 [9].

$$h = 435 \text{ km}$$

$$f = 13.9 \text{ GHz}$$

$$\beta_0 = 0.023 \text{ rad.}$$

We plot the computed results of σ_n^0/σ_c^0 versus $k\sigma$ in Fig. 2. Since an estimate of l for terrain may vary depending on topographic features, three cases of $kl = 7$, 49, and 100 are arbitrarily chosen.

Fig. 2 indicates that, depending on the particular roughness statistics, either the specular or the diffuse component can be of a dominant scattering process in backscattering. For instance, when $kl = 7$, scattering is dominantly specular. However, as kl increases to 49 and 100, the diffuse component can no longer be neglected.

Analyzing the Skylab S-193 altimeter data, Shapiro and Yaplee [7] made a very interesting observation: an anomalously strong specular return from terrain. Since estimates of the corresponding ground truth on σ and l are not available, it is difficult to quantitatively substantiate their observation. However, based on the theoretical behavior demonstrated in Fig. 2, we speculate that the coherent return can be dominant over the diffuse component provided the effective surface height correlation length (l) is much less than 35 cm (equivalently $kl = 100$). It is inter-

esting to note that the theoretical k_l estimates to fit L-band radar backscatter data from agricultural bareground are mostly less than 40 [5].

III. CONCLUSIONS

In case of such a high-altitude radar as space-borne altimeter, the ratio of diffuse to specular radar backscattering is found to increase as either the beamwidth, the surface height standard deviation, or the surface correlation length increases. Anomalous strong specular return from terrain in the Skylab altimeter experiment was examined and it was conjectured that the effective beamwidth was small enough to satisfy the condition for dominance by specular return. This occurs because the effective area involved in random scattering is reduced, thereby reducing the number of "small scatterers" contributing to the random phase return without reducing the specular component.

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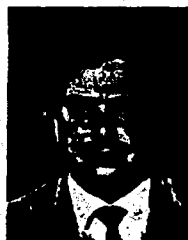
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Scattering from a Layered Medium Connected with Rough Interfaces: Matrix Doubling Method

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Abstract—A theoretical scattering model is developed that computes the scattered and transmitted intensities from an inhomogeneous layered medium above the half-space. A matrix doubling method technique is extended to handle multilayer scattering problems of which each scattering layer of spherical particles has rough boundary interfaces. Incoherent scattering is assumed in the formulation so that the Stokes vector representations are used to calculate the polarimetric multiple scattering effects. The scattering coefficients are computed for a two-layered Rayleigh scattering medium with a rough boundary. The developed scattering model of a radiative transfer approach is useful for scattering computations dealing with a random medium often encountered in active and passive microwave remote-sensing problems.

I. INTRODUCTION

INCOHERENT intensity scattering from a random inhomogeneous layered medium has been studied by many investigators in the area of active microwave remote sensing. One of the purposes of scattering studies is the medium profile inversion from data collected with remote-sensing devices. For instance, applications include snow wetness measurements and sea-ice classification using SAR imagery. In order to analyze microwave remotely sensed data, a variety of analytical techniques based on the field approaches [1]–[3] and intensity approaches [4]–[6] have been used.

When one deals with scattering from a layered scattering medium, a scatter model to accommodate the layering effect is needed. Recently, the radiative transfer technique [4] was taken and the theoretical formulation has been developed [7] that deals with scattering from an inhomogeneous multilayer connected by rough interfaces.

In this paper, we take the approach of the matrix doubling method [5] to develop a scattering model that computes polarimetric scattering intensities from a multilayer of spherical particles linked with rough boundaries. The existing matrix doubling method is extended to combine surface and volumetric scattering effects resulting from a multilayer with rough dielectric interfaces. In other words, we use the doubling technique on each individual layer, and then connect the results with rough boundary conditions. Based on the developed scattering model, the numerical results of backscattered intensity from two irregular Rayleigh layers are shown in Section III. In the next

section, an extended matrix doubling method is presented.

II. EXTENDED MATRIX DOUBLING METHOD

Consider a problem of scattering from two scattering thin layers embedded with spherical particles p and q whose dielectric constants are identical to each other (see Fig. 1). We assume the scattering from layers p and q are represented by corresponding scattering and transmission phase matrices S_p , T_p , S_p^* , T_p^* , and S_q , T_q , S_q^* , T_q^* . The starred quantities are the phase matrices when the direction of incidence is reversed. It is well known that the two scattering layers p and q can be combined into one equivalent layer, by means of the matrix doubling techniques [5]. The detailed derivation is available in [5]. The final results read

$$S_r = S_p + T_p^* S_q (I - S_p^* S_q)^{-1} T_p \quad (1a)$$

$$T_r = T_q (I - S_p^* S_q)^{-1} T_p \quad (1b)$$

$$S_r^* = S_p^* + T_p S_q^* (I - S_p S_q^*)^{-1} T_p^* \quad (1c)$$

$$T_r^* = T_q^* (I - S_p S_q^*)^{-1} T_p^* \quad (1d)$$

where S_r and T_r are the scattering and transmission phase matrices of optical depth $\tau_p + \tau_q$ and I is the identity matrix.

The size of S and T is 4×4 to account for polarization effects resulting from (1×4) Stokes vector representations. Note that the successive application of the above equations results in scattering and transmission matrices of any thickness of optical depth that one wishes to build.

Consider scattering from layers 1 and 2 depicted in Fig. 2. The average permittivities of layers 1 and 2 are ϵ_1 and ϵ_2 , respectively. The two scattering layers are joined together with rough dielectric interfaces. The process of intensity reflection and transmission across the dielectric boundary can be described by surface reflection and transmission phase matrices of (4×4) in size [5]. The explicit forms of surface phase matrices of the Kirchhoff rough surface are also given in [5].

For the sake of discussion, we assume that the boundary is detached from layer 1 and attached to layer 2. Layer 2 can then be considered as a two-layered medium having a scattering layer coated with a nonscattering dielectric layer above (see Fig. 3). From Fig. 3, the scattering and

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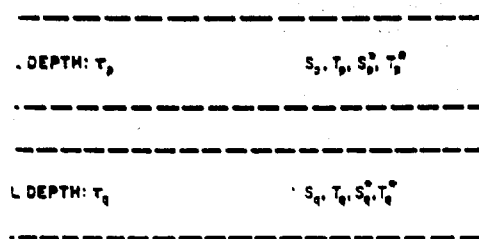


Fig. 1. Two Rayleigh scattering layers without dielectric boundaries.

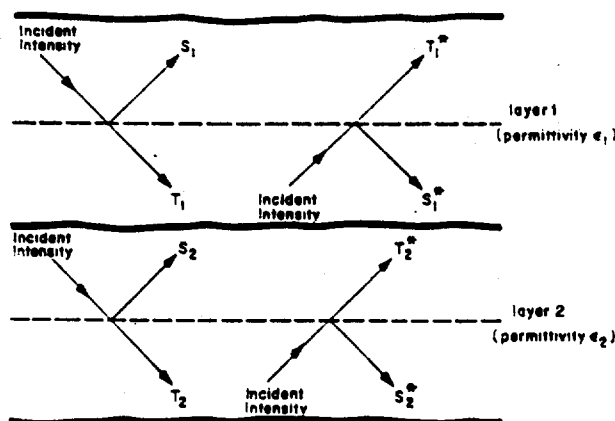


Fig. 2. Two Rayleigh scattering layers with dielectric boundaries.

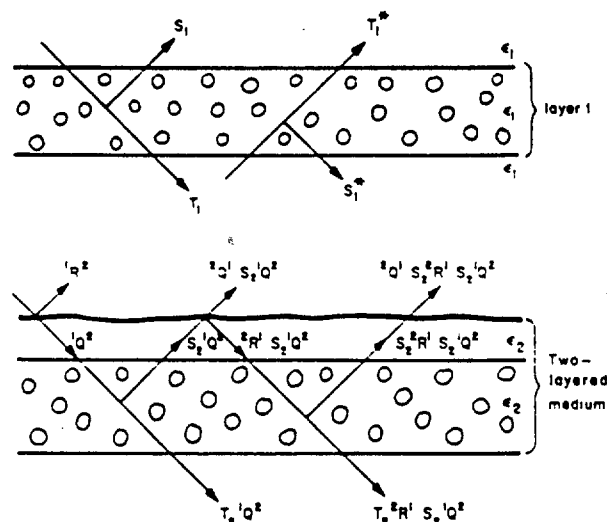


Fig. 3. Scattering and transmission phase matrices when incidence is from above layer.

transmission phase matrices read

$$\begin{aligned} \bar{S}_2 &= {}^1R^2 + {}^2Q^1 S_2 {}^1Q^2 + {}^2Q^1 S_2 {}^2R^1 S_2 {}^1Q^2 + \dots \\ &= {}^1R^2 + {}^2Q^1 (I - S_2 {}^2R^1)^{-1} S_2 {}^1Q^2 \end{aligned} \quad (2a)$$

$$\begin{aligned} \bar{T}_2 &= T_2 {}^1Q^2 + T_2 {}^2R^1 S_2 {}^1Q^2 + T_2 ({}^2R^1 S_2)^2 {}^1Q^2 + \dots \\ &= T_2 (I - {}^2R^1 S_2)^{-1} {}^1Q^2 \end{aligned} \quad (2b)$$

The notations " Q " and " R " denote the transmission and reflection phase matrices across media " m " and " n ."

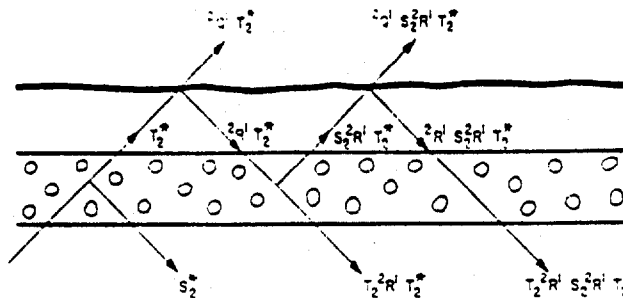


Fig. 4. Scattering and transmission phase matrices when incidence is from below layer.

When the incidence is reversed, a similar set of equations can be obtained (see Fig. 4).

$$\bar{S}_2^* = S_2^* + T_2 {}^2R^1 (I - S_2 {}^2R^1)^{-1} T_2^* \quad (2c)$$

$$\bar{T}_2^* = {}^2Q^1 (I - S_2 {}^2R^1)^{-1} T_2^* \quad (2d)$$

The scattering and transmission phase matrices S and T corresponding to a combined layer (i.e., layers 1 and 2) are obtained by substituting the phase matrices of layer 1 (S_1 , T_1 , S_1^* , and T_1^*) and the phase matrices of layer 2 (\bar{S}_2 , \bar{T}_2 , \bar{S}_2^* , \bar{T}_2^*) in the doubling equations (1).

$$S = S_1 + T_1 \bar{S}_2 (I - S_1^* \bar{S}_2)^{-1} T_1 \quad (3a)$$

$$T = \bar{T}_2 (I - S_1^* \bar{S}_2)^{-1} \quad (3b)$$

$$S^* = S_1^* + T_1 \bar{S}_2^* (I - S_1 \bar{S}_2^*)^{-1} T_1^* \quad (3c)$$

$$T^* = \bar{T}_2^* (I - S_1 \bar{S}_2^*)^{-1} T_1^* \quad (3d)$$

We refer to (3) as an extended matrix doubling equation. It is possible to compute intensity scattering and transmission from multilayers with dielectric interfaces by repeating the doubling process described in (3). As a check of (3), the following two special cases are in order. When a dielectric boundary between two scattering layers is absent (${}^1R^2 = {}^2R^1 = 0$, ${}^1Q^2 = {}^2Q^1 = I$), (3) reduces to (1). When the layers do not scatter, ($S_1 = S_2 = S_1^* = S_2^* = 0$, $T_1 = T_2 = T_1^* = T_2^* = I$), $S = {}^1R^2$, $T = {}^1Q^2$, $S^* = {}^2R^1$, and $T^* = {}^2Q^1$.

III. THEORETICAL BEHAVIOR OF SCATTER MODEL

As a numerical example, we compute scattering from two Rayleigh scattering layers joined by the Kirchhoff rough surface above the homogeneous half-space. This situation may arise when one is interested in backscattering from the irregular wet snow pack (optically thick, $\tau_2 = 2$) covered with the fluffy dry snow (optically thin, $\tau_1 = 0.5$). The geometry of the problem is illustrated in Fig. 5. In order for Rayleigh scattering assumption [8] to be valid, the size parameter (wave number \times radius of Rayleigh sphere) ≤ 0.3 . The VV polarized backscattering coefficient is plotted in Fig. 5 as a function of incidence angles. It is interesting to compare σ_{VV} with a sum of three major returns (volume scatter from first layer σ_v , atten-

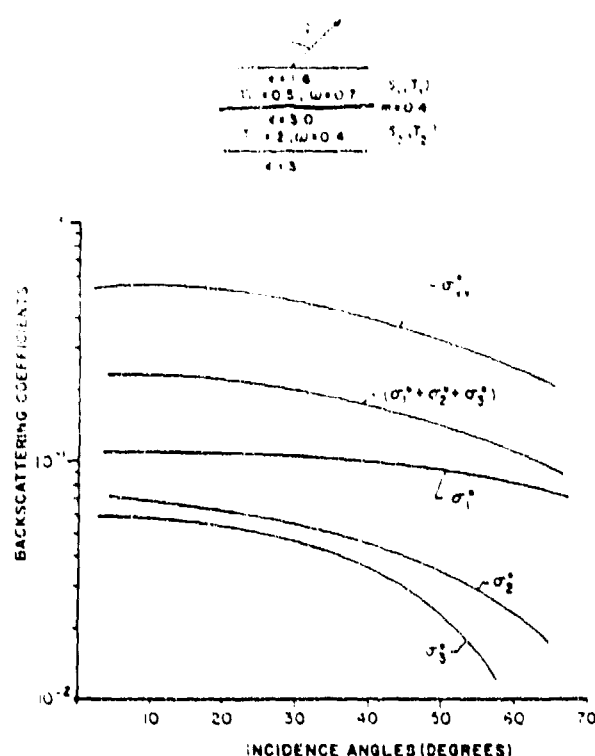


Fig. 5. Angular backscattering behavior of layered scattering medium.

uated volume scatter from second layer σ_2 , and attenuated surface backscatter from rough interface σ_3) where

$$\sigma_{VV} = S_1 + T_1^* \bar{S}_2 (I - S_1^* \bar{S}_2)^{-1} T_1$$

$$\sigma_1 = S_1$$

$$\sigma_2 = e^{-2\tau/\mu} S_2$$

$$\sigma_3 = e^{-2\tau/\mu} R^2$$

$$\mu = \cos \theta.$$

It is seen that a level difference of 3-4 dB exists between the exact solution and the sum of three major returns, thus implying that the level of multiple scattering between two scattering layers separated by the rough interface is appreciable.

IV. CONCLUSIONS

The matrix doubling technique for scattering from a multilayer connected with rough surfaces is developed. It is demonstrated that the extended doubling equation is an efficient computational algorithm for multilayer scattering problems.

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RE-DEVELOPMENT OF KENNAUGH'S TARGET CHARACTERISTIC POLARIZATION STATE THEORY
USING THE POLARIZATION TRANSFORMATION RATIO FORMALISM FOR THE COHERENT CASE

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ABSTRACT

The Kennaugh target characteristic polarization theory for the monostatic reciprocal coherent case is developed in greater detail, emphasizing the transformation of the scattering matrix under the change of polarization basis via the unitary transformation matrix formulated in terms of the polarization ratio ρ . Six characteristic polarization states are determined, and displayed on the Poincaré sphere and on power and phase plots. Several simple target cases are considered for demonstrating the applicability of this useful concept to radar target classification, imaging and identification.

I. INTRODUCTION

The use of characteristic polarization states in radar target applications has been a subject of recurring interest in recent years. The concept of characteristic polarization states was first introduced by Kennaugh [1] who demonstrated that there exist radar polarization states for which the radar receives minimum/maximum power. This mini/max polarization theory was extended

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in [2-6]. With the extensive use of this theory, it has been found that in the available literature, the characteristic polarization state theory (min/max polarization theory) has not been carried out rigorously and systematically and the question of uniqueness and validity was occasionally raised [5]. Different approaches were applied for determining these polarization states by using the voltage equation [1], the eigenvalue problem of the power scattering matrix [2,4], and the unitary transformation of the scattering matrix technique [3] to solve for four of the six characteristic polarization states (two COPOL- and two XPOL-Nulls).

Recently, Kostinski and Boerner [5] have critically reviewed the fundamentals of radar polarimetry, and pointed out that several ambiguities exist in the available literature, particularly, in relation to the use of the unitary transformation matrix, and the interpretation of the characteristic polarization theory. Because of the fact that this theory is being used in current investigations widely, a re-development of the characteristic polarization theory using exclusively the ρ -formulation and including the new findings is desirable in order to apply the theory more effectively in radar target phenomenology, identification and classification applications. Specifically, the applicability of applying this restricted ρ -formulation to the monostatic and the coherent scatterer case is analyzed.

II. FUNDAMENTALS OF RADAR POLARIMETRY

II.1 Polarization States and the Scattering Matrix [S]

A plane electromagnetic wave $\underline{E}(HV)$ propagating in the $+\hat{z}$ direction ($e^{j(\omega t - kz)}$), can be expressed in terms of the two orthonormal components in the \hat{h}_H and \hat{h}_V polarization basis as

$$\underline{E}(HV) = E_H \hat{n}_H + E_V \hat{n}_V = \cos\alpha \hat{n}_H + \sin\alpha e^{j\delta} \hat{n}_V \quad (1)$$

where E_H and E_V are the complex horizontally and vertically polarized components of the electric field, and the angles α and δ are defined in eqs.(2a,b). The polarization of the wave is described in the form of an ellipse as shown in Fig. 1a. The parameters ϕ and τ are the tilt and the ellipticity angles of the ellipse, respectively, given by

$$\tan 2\phi = 2|E_H||E_V|\cos\delta/(|E_H|^2 - |E_V|^2), \quad \sin 2\tau = 2|E_H||E_V|\sin\delta/(|E_H|^2 + |E_V|^2) \quad (2a)$$

and $\delta = \delta_V - \delta_H$ is the phase difference between the two orthogonal components, E_H and E_V . The polarization of the wave can also be described by the complex polarization ratio, ρ , which is defined by the ratio of the two orthogonal components [7] as shown in Fig. 1b as:

$$\rho = |\rho|e^{j\delta} = |E_V/E_H|e^{j(\delta_V - \delta_H)} = \tan\alpha e^{j\delta} \quad (2b)$$

where (α, δ) and (ϕ, τ) are related by the following equations [8]:

$$\cos 2\alpha = \cos 2\phi \cos 2\tau, \quad \tan \delta = \tan 2\tau / \sin 2\phi \quad (3a,b)$$

The parameter ρ is important in radar polarimetry, because it is used for representation of polarization signals on the Poincaré sphere [8] as shown in Fig. 1c. It is commonly denoted as the polarization transformation ratio.

When an electromagnetic wave of complex polarization ratio ρ illuminates a target, the complex polarization ratio of the scattered signal, in general, changes. This change of polarization states represents the characteristic properties of

the target as expressed by the scattering matrix [S]. The normalized monostatic and reciprocal scattering matrix ($S_{HV} = S_{VH}$) with relative phase in the orthonormal linear polarization basis (HV) is related to the incident field \underline{E}_i and the scattered field \underline{E}_s [1] as:

$$\underline{E}_s(HV) = [S(HV)] \underline{E}_i(HV), \quad [S(HV)] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}, \quad \begin{matrix} S_{HV} = S_{VH} \\ \text{(for monostatic and} \\ \text{reciprocal case)} \end{matrix} \quad (4)$$

II.2 Unitary Transformation Matrix In Terms Of The Polarization Ratio ρ

It is possible to transform the scattering matrix from one orthogonal polarization basis to another through a unitary matrix, which serves mainly two purposes: (i) extracting the useful information contained in the different polarization responses from the target, and (ii) making it possible to relate the results of the linear polarization radar of the polarization basis (HV) with the circular polarization and/or any elliptical polarization radar systems. A 2x2 general unitary transformation matrix [T] for transforming this linear polarization basis (HV) to another polarization basis (A'B') can be given [9] as:

$$\hat{h}(A'B') = [T] \hat{h}(HV), \quad [T] = \begin{bmatrix} \cos\alpha e^{j\psi_1} & \sin\alpha e^{j\psi_2} \\ -\sin\beta e^{j\psi_3} & \cos\beta e^{j\psi_4} \end{bmatrix} \quad (5)$$

with $\psi_1 - \psi_3 = \psi_2 - \psi_4$, and $\alpha = \beta$.

The unitary transformations have the important property of preserving the total power in the wave, which means that the inner product of the electric field vector is invariant under unitary transformation. A unitary transformation matrix [T] satisfies the following conditions:

$$[T]^*T = [T]^{-1}, \quad \det([T]) = 1 \quad (5)$$

The matrix of eq.(5) can be written as,

$$[T] = \frac{1}{\sqrt{1+\rho\rho^*}} \begin{bmatrix} e^{j\psi_1} & \rho e^{j\psi_1} \\ -\rho^* e^{j\psi_4} & e^{j\psi_4} \end{bmatrix}; \quad \cos\alpha = \frac{1}{\sqrt{1+\rho\rho^*}} \quad (7)$$

where $\rho = \tan\alpha e^{j\delta}$, $\delta = \psi_2 - \psi_1 = \psi_4 - \psi_3$, and $\det([T]) = e^{j(\psi_1+\psi_4)}$.

The phase of $\det([T])$ is arbitrary, and any values of ψ_1 and ψ_4 can be chosen. The simplest choice could be $\psi_1=0$, $\psi_4=0$. By fixing these values, the general phase information of the determinant is lost and the $[T]$ transformation matrix becomes restricted. Therefore, if the relative phase information between the columns of the 2×2 unitary matrix is not important, the restricted unitary matrix can be used in radar polarimetry without any reservation which is convenient because of the exclusive use of (2b) in the formulation of $[T]$.

In this paper, we have chosen another value of the phase of $\det([T])$, which satisfies the IEEE-Standard [7]. Let us consider an example of the unitary matrix, which transforms the linear (H-V) polarization basis to the circular (L-R) one [7] and vice versa as

$$[T_{1c}(HV \rightarrow LR)] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix}, \text{ and } [T_{c1}(LR \rightarrow HV)] = [T_{1c}]^{-1} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -j & j \end{bmatrix} \quad (8)$$

Both the matrices of eqs. (5) and (8) are unitary because they satisfy the conditions of eq.(6), and the determinant of eq.(8) is a complex number $\det([T_{1c}]) = e^{-j\pi/2}$. Using this result, eq. (7) is reformulated with $\psi_1+\psi_4 =$

$-\pi/2$, where we choose $\psi_1 = 0$, $\psi_2 = -\pi/2$, which gives the matrix [T] as

$$[T] = \frac{1}{\sqrt{1+\rho\rho^*}} \begin{bmatrix} 1 & \rho \\ j\rho^* & -j \end{bmatrix} \quad (9)$$

It is to be noted that [T] is the transformation matrix for the polarization basis. The vector transformation matrix [U] and the basis transformation matrix [T] are related by $[U] = [T]^T$, where [U] is related by the field vectors $\underline{E}(\text{HV})$ and $\underline{E}'(\text{A'B'})$ [3] as

$$\underline{E}(\text{HV}) = [U] \underline{E}'(\text{A'B'}), \quad [U] = \frac{1}{\sqrt{1+\rho\rho^*}} \begin{bmatrix} 1 & j\rho^* \\ \rho & -j \end{bmatrix} \quad (10)$$

which confirms with the formulation of the IEEE-Standard 149-1979 [7].

In the following, we shall make use of these formulations of (8) to (10) while keeping in mind that the two-parameter family of unitary matrices is not sufficiently general for certain classes of eigenvalue problems [5].

II.3 Transformation of the Scattering Matrix in the New Basis for the Monostatic and Reciprocal Case

Substituting eq. (10) into the voltage equation of the form $V = \underline{E}^T [S] \underline{E}$, the voltage equation in the new basis [3,10] can be written as:

$$V = V' = \underline{E}'^T [U]^T [S] [U] \underline{E}' = \underline{E}'^T [S'] \underline{E}' \quad (11)$$

This gives the scattering matrix in the new basis as,

$$[S'(A'B')] = [U]^T [S(HV)] [U], \quad [S'] = \begin{bmatrix} S'_{AA} & S'_{AB} \\ S'_{AB} & S'_{BB} \end{bmatrix}, \quad S'_{AB} = S'_{BA} \quad (12)$$

and, in this case, the following transformation invariants are satisfied:

$$|\det\{[S(HV)]\}| = |\det\{[S'(A'B')]\}|, \quad \text{Span}\{[S(HV)]\} = \text{Span}\{[S'(A'B')]\} \quad (13)$$

Now, substituting eq.(10) into eq.(12), the transformed scattering matrix elements in the new basis (A'B') can be written as

$$S'_{AA} = (1 + \rho\rho^*)^{-1} (\rho^2 S_{VV} + 2\rho S_{HV} + S_{HH}) \quad (14a)$$

$$S'_{AB} = S'_{BA} = -j(1 + \rho\rho^*)^{-1} (\rho S_{VV} + (1 - \rho\rho^*) S_{HV} - \rho^* S_{HH}) \quad (14b)$$

$$S'_{BB} = -(1 + \rho\rho^*)^{-1} (\rho^{*2} S_{HH} - 2\rho^* S_{HV} + S_{VV}) \quad (14c)$$

Similar equations appear in [3] with different scattering matrix element phases derived from the restricted unitary matrix, where the phase of the determinant of the unitary matrix was assumed to be zero. Note, that eqs. (14a-c) should not be considered as a simultaneous set of equations for ρ , but rather equations for $[S']$ for a given ρ .

The received power of the backscattered signal is proportional to the square of the amplitude of the voltage. If the proportionality constant is taken unity, then the power expression can be written [1] as

$$P = |V|^2 = |\underline{h}_r^T [S] \underline{h}_t|^2 = |\underline{h}_r'^T [S'] \underline{h}_t'|^2 \quad (15a)$$

where (') indicates the new basis, and \underline{h}_t and \underline{h}_t' are the polarization vectors of

the transmitting and receiving antennas, respectively. The co-polarized power can be calculated if $\underline{h}_r = \underline{h}_t = \underline{h}$ and $\underline{h}'_r = \underline{h}'_t = \underline{h}'$, then

$$P_c = |V_c|^2 = (\underline{h}^T(S)\underline{h})^2 = (\underline{h}'^T(S')\underline{h}')^2 \quad (15b)$$

Similarly, the cross-polarized power can be calculated if $\underline{h}_r = \underline{h}_{t\perp} = \underline{h}_\perp$ and $\underline{h}'_r = \underline{h}'_{t\perp} = \underline{h}'_\perp$ (\perp indicates the orthogonal vector), where the polarization ratios of \underline{h}_r , \underline{h}_t and \underline{h}'_r , \underline{h}'_t are related by $\rho_r \rho_t^* = -1$ and $\rho'_r \rho_t'^* = -1$. The cross-polarized power is then given as

$$P_x = |V_x|^2 = (\underline{h}_\perp^T(S)\underline{h})^2 = (\underline{h}'_\perp^T(S')\underline{h}')^2 \quad (15c)$$

III. FORMULATION OF THE CHARACTERISTIC POLARIZATION STATES (CPS)

In the previous section, the unitary transformation matrix was represented in terms of the complex transformation ratio, ρ , for transforming an electric field vector from one polarization basis to another. This change of polarization basis was demonstrated on the Poincaré sphere in terms of ρ ($\rho = \tan \alpha e^{j\delta}$), which provides the immediate visualization of the transformation parameters geometrically.

Now using the ρ -formulation, we determine the polarization states of the transmitted signal, for which the target returns maxima and minima in the co-polarized and cross-polarized channels, respectively. In this paper, we refer these polarization states as the target characteristic polarization states. The relative phase scattering matrix of the target can be recovered from these characteristic polarization states [2,3]. To determine these polarization states, we use the transformed scattering matrix in the new basis of eq. (14) and the

power expressions given by eq. (15) as follows:

III.1 Determination of the Polarization States (XPOL-Nulls), which produce Zero Power in the Cross-Polarized Channel (i.e., determine ρ for which $S_{AB} = 0$, or $P_x = 0$)

From eq.(14b), the XPOL Nulls in the H-V basis can be determined as

$$\rho_{xn1,2} = (-B \pm (B^2 - 4AC)^{1/2})/2A \quad (16)$$

where, $A = S_{HH}^* S_{HV} + S_{HV}^* S_{VV}$, $B = |S_{HH}|^2 - |S_{VV}|^2$, $C = -A^*$

$\rho_{xn1,2}$ can, in general, be written as $\tan \alpha_{xn1,2} \exp(j\delta_{xn1,2})$. It is readily shown that the XPOL-Nulls are orthonormal to each other, i.e., $\rho_{xn1} \rho_{xn2}^* = -1$. Now, the new scattering matrix in the XPOL-Null basis becomes diagonal and is expressed as:

$$[S_d] = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}, \quad \begin{aligned} \lambda_1 &= |\lambda_1| e^{j\phi_1} \\ \lambda_2 &= |\lambda_2| e^{j\phi_2} \end{aligned} \quad (17)$$

The values of λ_1 and λ_2 can be obtained by substituting $\rho = \rho_{xn1}$ in eqs.(14a-c). Since the order of eigenvalues has not been fixed, we may assume without loss of generality [2], that $|\lambda_1| \geq |\lambda_2|$. Thus, the powers corresponding to the XPOL-Nulls in the co-polarized channel are $P_{xn1}^C = |\lambda_1|^2$, and $P_{xn2}^C = |\lambda_2|^2$.

III.2 Determination of the Polarization States (COPOL Nulls), which produce Zero Power in the Co-Polarized Channel (i.e. find ρ for which $S_{AA} = 0$, or $P_C = 0$)

From eq.(14a), the COPOL-Nulls in the H-V basis are given by

$$\rho_{cn1,2} = (-S_{HV} \pm (S_{HV}^2 - S_{HH}S_{VV})^{1/2})/S_{VV} \quad (18)$$

The COPOL-Nulls can also be calculated by considering [S] in the XPOL-Null basis.

Taking $P_c = 0$ in eq.(15b), i.e. $P_c = |\underline{h}'^T [S_d] \underline{h}'|^2 = 0$, which gives

$$\rho'^2 = -\lambda_1/\lambda_2 = |\lambda_1/\lambda_2| e^{j(\phi_1 - \phi_2 + \pi)}$$

Let, $\tan \gamma = (|\lambda_2/\lambda_1|)^{1/2}$, $\phi_1 - \phi_2 = 4\nu$, and $\psi = 90^\circ - \gamma$

then the COPOL-Nulls in the XPOL-Null basis are

$$\rho'_{cn1,2} = \pm \tan \psi e^{j(2\nu + \pi/2)} \quad (19)$$

where (') indicates the new basis. Eq.(19) indicates that the magnitudes of the polarization ratios $\rho'_{cn1,2}$ are equal, and the phase difference between them is equal to π . Using these results, it is straightforward to represent the diagonal matrix $[S_d]$ of eq.(17) in terms of the Huynen [2] target parameters.

Let, $\phi_1 = \xi + 2\nu$, $\phi_2 = \xi - 2\nu$, $|\lambda_1| = m$, and $\xi = (\phi_1 + \phi_2)/2$

then $[S_d]$ can be rewritten as

$$[S_d] = e^{j\xi} \begin{bmatrix} m e^{j2\nu} & 0 \\ 0 & m \tan^2 \gamma e^{-j2\nu} \end{bmatrix} \quad (20)$$

The matrix of eq.(20) is equivalent to Huynen's [2] diagonal matrix, where the parameter m^2 represents the co-polarized power return when the signal transmitted

is not depolarized; $4v$ represents the phase difference between the two diagonal elements λ_1 and λ_2 (v was named target skip angle by Huynen [2]) and its range is $-45^\circ \leq v \leq 45^\circ$; $\tan^2 \gamma$ represents the ratio of the amplitudes of λ_1 and λ_2 (γ was named target characteristic angle by Huynen [2]), and its range is $0 \leq \gamma \leq 45^\circ$; and ξ represents the absolute phase¹.

The power return in the cross-polarized channel corresponding to the COPOL-Nulls can be calculated from eq.(15b) as

$$P_{cn1,2}^x = m^2 \tan^2 \gamma \quad (21)$$

III.3 Determination of the Polarization States (COPOL-Max), which produce Maximum Power in The Co-Polarized Channel (i.e., find ρ for which P_c is maximum)

From eq.(15b)

$$P_m^C = P_c = (1 + \rho' \rho'^*)^{-2} (\rho'^2 \rho'^*{}^2 |\lambda_2|^2 + \rho'^2 \lambda_1^* \lambda_2 + \rho'^*{}^2 \lambda_1 \lambda_2^* + |\lambda_1|^2) \quad (22a)$$

$$P_m^C \text{ is maximum when } \rho' = \rho'_{cm} = 0, \text{ i.e. } P_m^C = |\lambda_1|^2 = m^2 \quad (22b)$$

Note that $\rho'_{cm} = 0$ corresponds to the XPOL-Null basis, and the power associated with it is $|\lambda_1|^2$. Referring to the XPOL-Nulls in the H-V basis as derived in (16), the power associated with one of the XPOL-Nulls (ρ_{xn1}) is also $|\lambda_1|^2$. Thus the value of $\rho'_{cm} = 0$ in the XPOL-Null basis is equal to ρ_{xn1} in the H-V basis. Therefore, one of the XPOL-Nulls corresponds to the maximum return in the co-polarized channel (i.e., $P_{xn1}^C = P_m^C$), while the other XPOL-Null corresponds to the power, $P_{xn2}^C = m^2 \tan^4 \gamma$. The co-polarized power received for both the XPOL-Nulls

¹ We would like to mention that the spin matrices used by Huynen [2] for the transformations of the polarization vectors (spinors) and the scattering matrices are not considered in this paper.

becomes equal when $\gamma = 45^\circ$.

III.4 Determination of the polarization states (XPOL-Maxs), which produce maximum power return in the cross-polarized channel (i.e., find ρ for which P_x is maximum)

Eq.(15c) gives

$$P_{xm}^x = P_x = |(1 + \rho' \rho'^*)^{-1} m(e^{j(2\nu)} \rho'^* - \tan^2 \gamma e^{-j(2\nu)} \rho')|^2$$

which is maximized when the right most term is negatively large. This occurs when

$$\rho' = \rho'_{xm1,2} = \pm e^{j(2\nu + \pi/2)} \quad (23)$$

and the maximum power in the cross-polarized and co-polarized channels can respectively be derived as

$$P_{xm1,2}^x = m^2 / (4 \cos^4 \gamma), \quad P_{xm1,2}^c = m^2 \cos^2 2\gamma / (4 \cos^4 \gamma) \quad (24a,b)$$

Note, that ρ'_{xm1} and ρ'_{xm2} are also orthonormal to each other, i.e., $\rho'_{xm1} \rho'_{xm2}^* = -1$, and the phase difference between them is π . Comparing eqs. (21) and (24a), it is observed that the power returns in the cross-polarized channel at the COPOL-Nulls and the XPOL-Maxs are not identical, i.e. $P_{cn1,2}^x \neq P_{xm1,2}^x$, which implies that the power return in the cross-polarized channel at the COPOL-Nulls is not maximum. Similarly from eq. (24b) the power return in the co-polarized channel at the XPOL-Maxs is not equal to zero, i.e. $P_{xm1,2}^c \neq 0$. However only if the characteristic angle, γ , becomes $\gamma = 45^\circ$, the COPOL-Nulls and the XPOL-Maxs do occur at identical locations. In this case the COPOL-Nulls are true power nulls in the co-polarized channel and the XPOL-Maxs are true power maxima in the

cross-polarized channel.

III.5 Interrelation among the Six Characteristic Polarization States

From the above discussion, we have seen that there are two polarization states ($\rho_{xnl,2}$) of eq. (16) for zero cross-polarized return; two ($\rho'_{cnl,2}$) of eq. (19) for zero co-polarized return; one (ρ'_{cm}) of eq. (22b) for maximum co-polarized return; and two ($\rho'_{xnl,2}$) of eq. (23) for maximum cross-polarized return. It is found from eqs. (17a) and (22b) that the COPOL-Max (ρ'_{cm}) is always equal to one of the XPOL-Nulls (ρ_{xnl}). Thus, there are only six polarization states which may be denoted as "Characteristic Polarization States (CPS)". These results are summarized in Table 1.

Let us represent the orthonormal XPOL-Nulls ($\rho_{xnl,2}$) of eq. (16) by the antipodal points X_1 and X_2 on the Poincaré sphere as shown in Fig. 2. According to the Poincaré sphere rules [4,8], if the polarization ratios of the polarization states are given in the new basis (X_1, X_2), then the equal-valued magnitudes of the polarization ratios lie on the circle around the diameter joining X_1 and X_2 , and their phases represent the rotation of the points around the diameter ($X_1 X_2$) [4]. Following these rules, the COPOL-Nulls ($\rho'_{cnl,2}$) of eq. (19) which are given in the XPOL-Null basis can be represented by the points C_1 and C_2 on the COPOL-Null cone of the Poincaré sphere as shown in Fig. 2. Since the phase difference between the COPOL-Nulls of eq. (19) is π , the difference in rotations of the points C_1, C_2 about the diameter $X_1 X_2$ is also equal to π and therefore, they are located on the same great circle. Further, since according to (19) the magnitudes ($\tan \psi$) of the COPOL-Nulls are equal, the XPOL-Nulls (X_1, X_2) bisect the angle C_1-O-C_2 (where O is the origin of the sphere) made by the COPOL-Nulls at the origin of the sphere. Now the question is to which of the XPOL-Nulls ($X_1,$

X_2) are the COPOL-Nulls (C_1, C_2) closer? Since the spread of the COPOL-Nulls with respect to X_1 according to eq. (19) is $2\psi = 180^\circ - 2\gamma$, where $0^\circ \leq \gamma \leq 45^\circ$, the range of 2ψ will be $90^\circ \leq 2\psi \leq 180^\circ$. This implies that the COPOL-Nulls will be closer to X_2 , which is orthonormal to X_1 according to (16). Note that the XPOL-Null (X_1) represents the maximum power return in the co-polarized channel. Now let us represent the XPOL-Maxs of eq. (23) by the points S_1 and S_2 about the point X_1 on the Poincaré sphere. Due to the orthonormality of the XPOL-Maxs, they are represented by the antipodal points on the sphere. Since according to (23) their amplitudes are equal and the phase difference is π , the XPOL-Maxs lie on the same great circle, where the diameter S_1S_2 is perpendicular to the diameter X_1X_2 according to (23). Thus, summarizing above relationships, the interesting property results that for the monostatic, reciprocal (symmetric matrix) case, all of the six characteristic polarization states lie on 'One Main Circle' and they form a "Polarization Fork" with one handle and five prongs as shown² in Fig. 2. However, we emphasize that for the general bistatic (asymmetric matrix) case, it was shown in [4] that two main circles are required for relating the resulting characteristic polarization states. They can also be determined by using the Three-Stage-Procedure introduced in [5].

IV. GRAPHICAL REPRESENTATION OF A TARGET'S SCATTERING MATRIX BEHAVIOR AS A FUNCTION OF THE TRANSCEIVER POLARIZATIONS: THE POLARIZATION FORK, THE CO-/CROSS-POLARIZED POWER SPECTRA, AND THE RELATIVE CO-/CROSS-POLARIZATION PHASES

For a discrete mini-max polarimetric target description, as given in the previous section, it is found expedient to provide three-dimensional continuous plots of the received powers in the co-polarized (A) and the cross-polarized (B) channels, i.e. $P_c = |S_{AA}(\phi, \tau)|^2$ and $P_x = |S_{AB}(\phi, \tau)|^2$ according to eqs. (14a,b, 15a,b), as

² Note, our polarization fork differs from that introduced by Huynen [2], who defined the fork by one handle and three prongs by neglecting the two XPOL-Maxs.

well as the relative co-/cross-polarization phase differences $\psi(\phi, \tau) = |\phi_{AA} - \phi_{BB}|$ and $\chi(\phi, \tau) = |\phi_{AA} - \phi_{AB}|$ according to eqs. (A.3) of Appendix. These are functions of the general transceiver polarization states (ϕ, τ) and identify the characteristic polarization states on these maps.

In order to graphically display these polarimetric scattering matrix properties, the Poincaré sphere was found to be appealing only for presenting the polarization fork (Fig. 2); for displaying power spectral and relative polarization phase information it was found inadequate. Therefore, recourse was taken to linear rectangular (ϕ, τ) maps [5,11]. It was found that three-dimensional perspective planar plots are well-suited for plotting the power spectra, as was recently proposed in [5] and also used in [11]. Multiple-color imagery are for displaying the relative co-/cross-polarization phase difference onto the linear rectangular (ϕ, τ) maps.

All of above described polarimetric display methods are illustrated in Fig. 3 for one general symmetric scattering matrix case, selected from Kostinski and Boerner [5] and described in Fig. 3a, where Fig. 3b presents the polarization fork, Figs. 3c,d display the co-/cross-polarization power spectral plots $|S_{AA}(\phi, \tau)|^2$, $|S_{AB}(\phi, \tau)|^2$, and Figs. 3e,f the relative co-/cross-polarization phase plots $\psi(\phi, \tau)$, $\chi(\phi, \tau)$, respectively. From simultaneous inspection of all of these displays, we observe that the polarization fork together with the power spectral and relative co-/cross-polarization phase plots well describes the scattering matrix properties and that the introduction of the two additional XPOL-Maxs improves the interpretation of the target characteristic polarization states description. Also, the relative co-polarization phase plots reveal that for more complicated shapes, polarimetric phase calibration errors may become very

critical in establishing the polarization fork properties.

V. APPLICATIONS TO RADAR TARGET CLASSIFICATION

We consider a few examples of simple canonical radar targets to illustrate the usefulness of the new formulation of the characteristic polarization states with the graphical representation of the polarization fork, co-/cross-polarization power spectra and the relative co-/cross-polarization phases. For all examples, their scattering matrices and Huynen parameters are given in Table 2; the polarization forks and power spectra are shown in Figs. 4-7; and all the relative co-/cross-polarization phases are collectively shown in Fig. 8. Examples of more complicated targets are treated in [12,13].

V.1 Metallic Flat Plate or Sphere

This example is illustrated in Fig. 4a,b. Here, only the co-polarization power spectral plot is shown because the cross-polarization power spectral plot is the identical configuration to the co-polarization power spectral plot if one is viewed from the top and the other from the bottom side. The features of the flat plate are expected to occur in the radar images for specular reflections, e.g., smooth surfaces, spherical targets, etc.

V.2 Dihedral Corner Reflection (Trough)

This target (two planes intersecting at 90°) is illustrated in Fig. 4c,d. In this example, the incident field suffers two reflections (i.e., double bounce). The co-/cross-polarization power spectral plots are also identical in this case if one is viewed from the top and the other from the bottom side. These kinds of features of the target are expected in the radar images of rough surfaces containing corner reflectors.

V.3 Linear Targets (Dipole)

Three cases of linear targets (dipoles): horizontal dipole, vertical dipole, and dipole at 45° orientation are considered. Only a dipole at 45° orientation is illustrated in Fig. 5. The features of the horizontal and vertical dipoles can be obtained by rotating the great circle of the Poincaré sphere in the azimuthal direction. For horizontal dipole, the x_1 should lie at the H-polarization state, and for vertical dipole, x_1 should lie at V-polarization state [12]. These type of features of the targets are expected to occur in the radar images of a dipole cloud or whenever scattering from electrically thin extended straight conducting wire or from sharp edges is encountered such as telephone lines, railroads, etc., in polarimetric SAR imaging.

V.4 Huynen's Artificial Helical Targets

Huynen's metallic helical targets with right and left screws are considered. In Fig. 6, only the helical target with right screw is illustrated. In this example, if the polarization of the incident wave is right hand circular, then the return signal will be right hand circular only. On the other hand, if the polarization of the incident wave is left hand circular, then the return signal will be zero. This shows that the right screw helix behaves like a right hand circular dipole in the circular polarization basis (see Table 2).

Similarly, it can be shown that the left hand screw helix behaves like a left hand circular dipole in the circular polarization basis [12].

V.5 Quarter-Wave Reflectors

Two types of quarter-wave reflectors: one in which the, vertically polarized

signal differs from the horizontally polarized signal by 90° phase and in another by -90° phase are considered. In Fig. 7, only the quarter wave reflector with 90° phase is illustrated. The detail of the other reflector with -90° phase is discussed in [12]. These features of the targets are expected in the radar images of the perfect conductors coated with dielectric material, which for a certain critical coating depth behave like a quarter-wave reflector.

V.6 Comparative Remarks of the Examples Considered Above

V.6.1 Target Characteristic Angle γ :

From the examples considered above, it can be interpreted that when the characteristic angle, γ , is zero, both the COPOL-Nulls become equal to the XPOL-Null-2 (X_2) (see the examples of the dipoles and the helices), i.e., they become antipodal to the COPOL-Max. When the target characteristic angle becomes $\gamma = 45^\circ$, the COPOL-Nulls become equal to the XPOL-Maxs (see the examples of the flat plate and the corner reflector). Therefore, the non-zero value of the angle, γ , in the range $0 < \gamma < 45^\circ$ will separate all the characteristic polarization states at different locations on the Poincaré sphere, as was shown for the general example considered in Section IV.

V.6.2 Target Skip Angle, ν :

It is noticed that when the skip angle becomes 0° (flat plate), the target acts as a single (odd) bounce reflector, on the other hand, when the skip angle becomes $\nu = 45^\circ$ (corner reflector), the target acts as a double (even) bounce reflector. If the skip angle becomes $\nu = \pi/8$, the target acts as a quarter-wave reflector as shown in Section V.5.

In comparing the cases of the horizontal/vertical dipoles and the left/-right screw helices, it is found that the values of $m = 1$, $\gamma = 0^\circ$ and $\nu = \text{'arbitrary'}$

are identical in both cases. This is because the linear dipoles in the H-V basis are the dual set of the helical targets in the circular basis.

V.6.3 Relative Co-/Cross-Polarization Phases:

From the relative co-/cross-polarization phase plots illustrated in Fig. 8, it is observed that at the COPOL-Nulls and /or XPOL-Nulls the relative co-/cross-polarization phases become undefined. They are clearly identifiable by those points where all the color contours converge. However, these features are not observed in the case of a flat plate. In the example of the corner reflector and quarter-wave reflectors, where the XPOL-Maxs are identical to the COPOL-Nulls, the relative phases at the XPOL-Maxs behave in the same manner as they do at the COPOL-Nulls, but in general the undefined relative phase behavior at the XPOL-Maxs is not observed.

A possible explanation of the undefined phase behavior at the COPOL-/XPOL-Nulls is found by considering that the co-polarized element (S_{AA}) of the scattering matrix becomes zero at the COPOL-Nulls, where the phase of the element, S_{AA} , is not defined. Similarly, at the XPOL-Nulls, the off-diagonal elements (S_{AB}) of the scattering matrix become zero, so it should make the relative cross-polarization phase become undefined.

We illustrate the relative co-/cross-polarization phase behavior for a general example of Fig. 8.10a,b (also Fig. 3e,f). At the COPOL-Nulls (C_1, C_2), the relative co-/cross-polarization phases are undefined, and at the XPOL-Nulls (X_1, X_2), the co-polarization phases of Fig. 8.10a have finite values. The cross-polarization phases of Fig. 8.10b have undefined values. But both the phases are finite at the XPOL-Maxs (S_1, S_2).

In all the examples considered, we have shown that the Poincaré sphere representation provides the information about the discrete locations of the characteristic polarization states in the form of a polarization fork, whose parameters are m , v , γ as discussed in Section III.5. The information about the power returns at these locations cannot be easily obtained from this representation. On the other hand, the power return in the co-/cross-polarized channels at these characteristic states are obtained from the co-/cross-polarization power spectral and relative co-/cross-polarization phase plots. The polarization fork properties of the characteristic polarization states cannot be easily interpreted from these plots. Thus, in order to obtain a complete picture of the polarimetric behavior of a target as a function of the interrogating polarization state, both of the representations introduced here are deemed necessary.

VI. CRITICAL ASSESSMENT OF THE ρ -TRANSFORMATION FORMALISM

In this paper, a 2×2 general unitary transformation matrix with four parameters has been reduced to two parameters by introducing a complex polarization ratio, ρ . By doing so, the unitary matrix becomes restricted because the information about the relative phase between the columns of the unitary matrix is lost. However, in radar polarimetry, if the two polarization vectors with different absolute phases are identical³, then the restricted 2×2 unitary matrix is sufficient to transform the polarization vector from one polarization basis to another, and the scattering matrix $[S]$ can therefore be transformed from one polarization basis to another by using the same restricted unitary matrix. It is to be noted that the congruence transformation, eq.(12), which was used to diagonalize the symmetric scattering matrix in the monostatic and reciprocal case, cannot be applied to the bistatic case (for which the scattering matrix is asymmetrical in

³ Consider two polarization vectors $\begin{pmatrix} 1 \\ -j \end{pmatrix}$ and $\begin{pmatrix} j \\ 1 \end{pmatrix} = j \begin{pmatrix} 1 \\ -j \end{pmatrix}$. Both the vectors represent the right-hand-circular polarization and can be represented by a point (RHC) on the Poincaré sphere. Therefore, the relative phase between the two polarization vectors is unimportant.

general). Rather, the two distinct (congruence and similarity) unitary transformation matrices introduced in [5] should be considered as discussed in [4,5].

VII. CONCLUSION

The restricted unitary transformation matrix formulated in terms of σ is modified according to IEEE standards [3,4]. Using this unitary transformation matrix, the six characteristic polarization states are determined by the transformation of the scattering matrix from one polarization basis to another basis. These characteristic polarization states lie on one great circle on the Poincaré sphere and produce the pattern of the "Polarization Fork", with one handle representing the maximum co-polarized return, and the five prongs representing the powers in the rest of the characteristic polarization states.

The new polarimetric plots on the co-/cross-polarization power spectra and relative co-/cross-polarization phases are introduced, and it is emphasized by demonstrating few simple target models that for a complete picture of the polarimetric behavior of a target as a function of the transceiver polarization state, all the three representations are important.

This theory can further be extended using a coherency matrix formulation for an ensemble of scatterers (e.g. distributed target) for identifying the partially coherent properties of the resulting clutter, and detecting a target in the presence of such clutter, which is treated in [14].

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APPENDIX

Expressions used for Calculating the Relative Co-/Cross-Polarization Phase Plots

Whereas, in the calculation of the power spectral plots, eqs. (14a-c) have been used in calculating the relative co-/cross-polarization phase plots introduced in Sections IV and V.7, eqs. (14a-c) are not used because these equations are derived from the restricted unitary matrix, where the relative phase of the two column vectors is discarded. Hence for the relative phase plots, we use the expressions as derived below.

The transmitted field in terms of the polarization parameters ϕ and τ can be expressed [2] as

$$\underline{h}(\phi, \tau) = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\tau \\ j\sin\tau \end{bmatrix} \quad (\text{A.1})$$

Then the polarization orthonormal to eq. (A.1) can be written as

$$\underline{h}_\perp(\phi, \tau) = \underline{h}(\phi + \pi/2, -\tau) = \begin{bmatrix} -\sin\phi & -\cos\phi \\ \cos\phi & -\sin\phi \end{bmatrix} \begin{bmatrix} \cos\tau \\ -j\sin\tau \end{bmatrix} \quad (\text{A.2})$$

Thus, when the signal with polarization states $\underline{h}(\phi, \tau)$ and $\underline{h}_\perp(\phi, \tau)$ are transmitted respectively, the voltages in the co-polarization channel, A, and the cross-polarization channel, B become

$$V_{AA} = \underline{h}^T [S(HV)] \underline{h}, \quad V_{AB} = \underline{h}_\perp^T [S(HV)] \underline{h}, \quad V_{BB} = \underline{h}_\perp^T [S(HV)] \underline{h}_\perp, \quad V_{BA} = \underline{h}^T [S(HV)] \underline{h}_\perp$$

and the relative co-polarization phase, $\phi(\phi, \tau)$ and the cross-polarization phase, $\Psi(\phi, \tau)$ are defined by

$$\phi(\phi, \tau) = |\phi_{AA} - \phi_{BB}|, \quad \chi_1(\phi, \tau) = |\phi_{AA} - \phi_{AB}|, \quad \chi_2(\phi, \tau) = |\phi_{BB} - \phi_{BA}| \quad (\text{A.3})$$

where $\phi_{AA} = \arg(V_{AA})$, $\phi_{BB} = \arg(V_{BB})$, $\phi_{AB} = \arg(V_{AB})$, and $\phi_{BA} = \arg(V_{BA})$, and only $\chi(\phi, \tau) = \chi_1(\phi, \tau)$ was presented in Sections IV and V.7.

TABLE 1: Characteristic Polarization States and Their Related Power Expressions in the Co-Polarized and Cross-Polarized Channels

| Characteristic Polarization States | Polarization Ratios | Received Power | |
|------------------------------------|---|--|---|
| | | Co-Polarized | Cross-Polarized |
| XPOL-Nulls (H-V Basis) | $\rho_{xn1,2} = (-B \pm \sqrt{B^2 - 4AC})/2A$ where $A = -e^* = S_{HH}^* S_{HV} + S_{HV}^* S_{VV}$ $B = S_{HH} ^2 - S_{VV} ^2$ | $P_{xn1}^C = m^2$ $P_{xn2}^C = m^2 \tan^2 \gamma$ | $P_{xn1}^X = 0$ $P_{xn2}^X = 0$ |
| COPOL-Max (H-V Basis) | $\rho_m = \rho_{xn1}$ | $P_m^C = P_{xn1}^C = m^2$ | $P_m^X = 0$ |
| COPOL-Nulls (XPOL-Null Basis) | $\rho'_{cn1,2} = \pm \tan(90 - \gamma) e^{j(2\psi + \pi/2)}$ | $P_{cn1,2}^C = 0$ | $P_{cn1,2}^X = m^2 \tan^2 \gamma$ |
| XPOL-Maxs (XPOL-Null Basis) | $\rho'_{xm1,2} = \pm e^{j(2\psi + \pi/2)}$ | $P_{xm1,2}^C = \frac{m^2 \cos^2 2\gamma}{4 \cos^4 \gamma}$ | $P_{xm1,2}^X = \frac{m^2}{4 \cos^4 \gamma}$ |

TABLE 2: Unitary Transformations of the Scattering Matrix $S(HV)$ in the H-V Basis to the Circular Basis $S(LR)$ by Using $S(LR) = [U]T[S^{(HV)}][U]^T$

Where according to (8) $[U] = [T_{1c}(HV \rightarrow LR)]^T = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$, and

Huynen parameters (m, ν, γ)

| | H-V Basis | LHC-RHC Basis | m, ν, γ |
|---|--|--|---|
| Metallic Sphere or Flat Plate (Case V.1) | $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ | $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ | $m = 1$ $\nu = 0^\circ$ $\gamma = 45^\circ$ |
| Corner Reflector (Case V.2) | $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$ | $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ | $m = 1$ $\nu = 45^\circ$ $\gamma = 45^\circ$ |
| Dipole (Case V.3) | | | |
| (i) Horizontal | $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ | $\frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ | $m = 1$ $\nu = \text{arbitrary}$ $\gamma = 0^\circ$ |
| (ii) Vertical | $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ | $\frac{1}{2} \begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix}$ | $m = 1$ $\nu = \text{arbitrary}$ $\gamma = 0^\circ$ |
| (iii) 45° oriented | $\frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ | $\frac{1}{2} \begin{bmatrix} j & 1 \\ 1 & -j \end{bmatrix}$ | $m = 1$ $\nu = \text{arbitrary}$ $\gamma = 0^\circ$ |
| Helix (Right Screw) (Case V.4) | $\frac{1}{2} \begin{bmatrix} 1 & -j \\ -j & -1 \end{bmatrix}$ | $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ | $m = 1$ $\nu = \text{arbitrary}$ $\gamma = 0^\circ$ |
| Helix (Left Screw) | $\frac{1}{2} \begin{bmatrix} 1 & j \\ j & -1 \end{bmatrix}$ | $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ | $m = 1$ $\nu = \text{arbitrary}$ $\gamma = 0^\circ$ |
| Quarter-Wave Reflector with 90° Phase, (Case V.5) | $\begin{bmatrix} 1 & 0 \\ 0 & j \end{bmatrix}$ | $\frac{e^{-j\pi/4}}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}$ | $m = 1$ $\nu = -\pi/8$ $\gamma = 45^\circ$ |
| Quarter-Wave Reflector with -90° Phase | $\begin{bmatrix} 1 & 0 \\ 0 & -j \end{bmatrix}$ | $\frac{e^{j\pi/4}}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}$ | $m = 1$ $\nu = \pi/8$ $\gamma = 45^\circ$ |
| General Target (Fig. 3) | $\begin{bmatrix} 2j & \frac{1}{2} \\ \frac{1}{2} & -j \end{bmatrix}$ | $\begin{bmatrix} 2j & \frac{j}{2} \\ \frac{j}{2} & j \end{bmatrix}$ | $m = 2.2$ $\nu = 0^\circ$ $\gamma = 31.1^\circ$ |

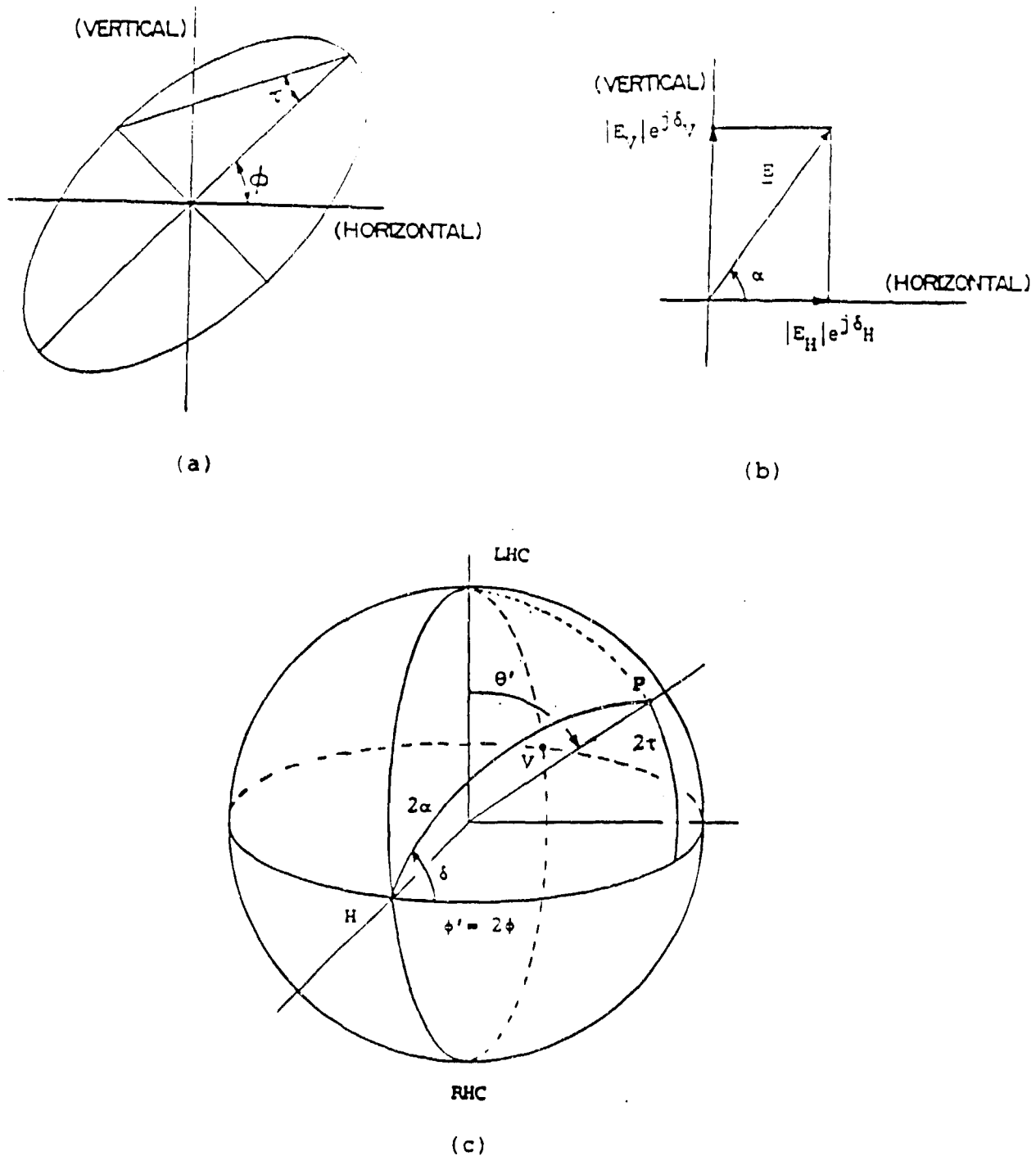


Fig. 1: (a) Parametric Presentation of the Polarization Ellipse, (b) Representation of the Polarization State in the Horizontal-Vertical (H-V) Basis, (c) Representation of a Polarization State on the Poincaré Sphere with Definition of Angles (α, δ) and (ϕ, τ) of the Polarization State Presentations of Figs. 2a,b According to Eqs. (2a,b) and (3a,b) (Spherical Azimuth Angle $\phi' = 2\phi$, Spherical Polar Angle $\theta' = \frac{\pi}{2} - 2\tau$)

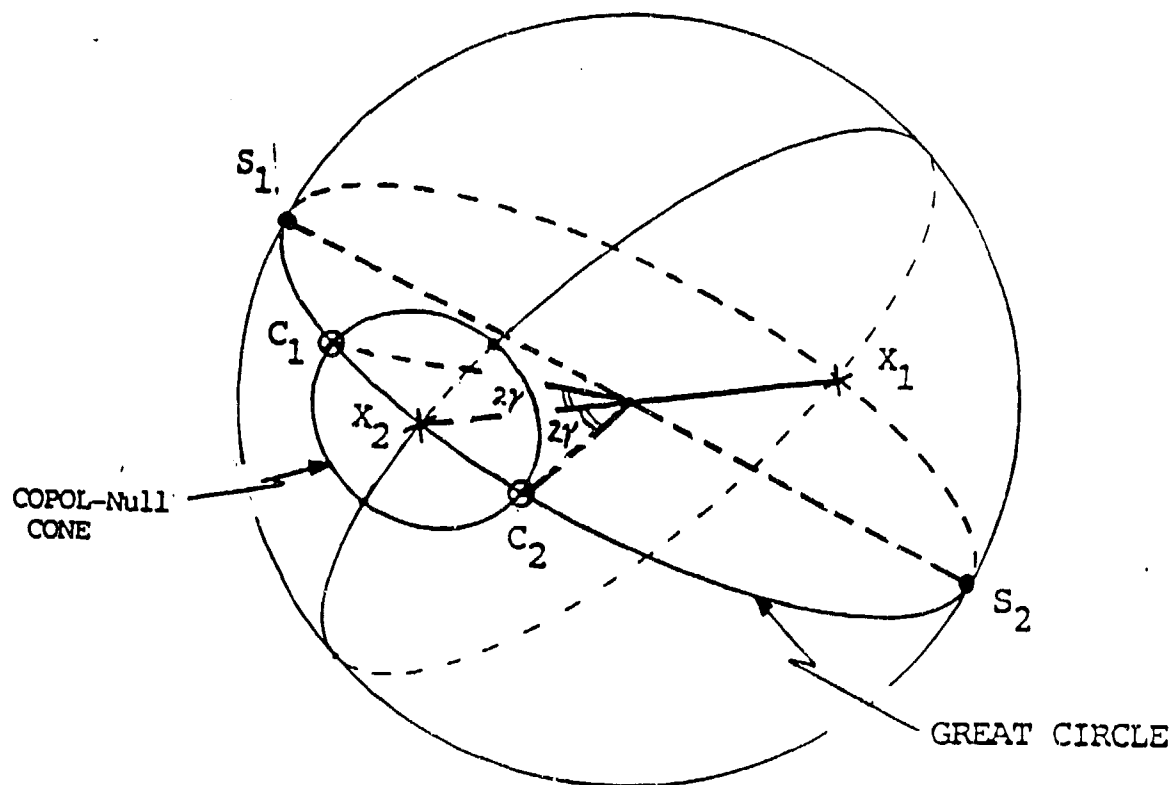


Fig. 2: Representation of the Characteristic Polarization States on the Poincaré Sphere (XPOL-Nulls: $X_{1,2}$; COPOL-Nulls: $C_{1,2}$; XPOL-Maxs: $S_{1,2}$; Target Characteristic Angle: γ)

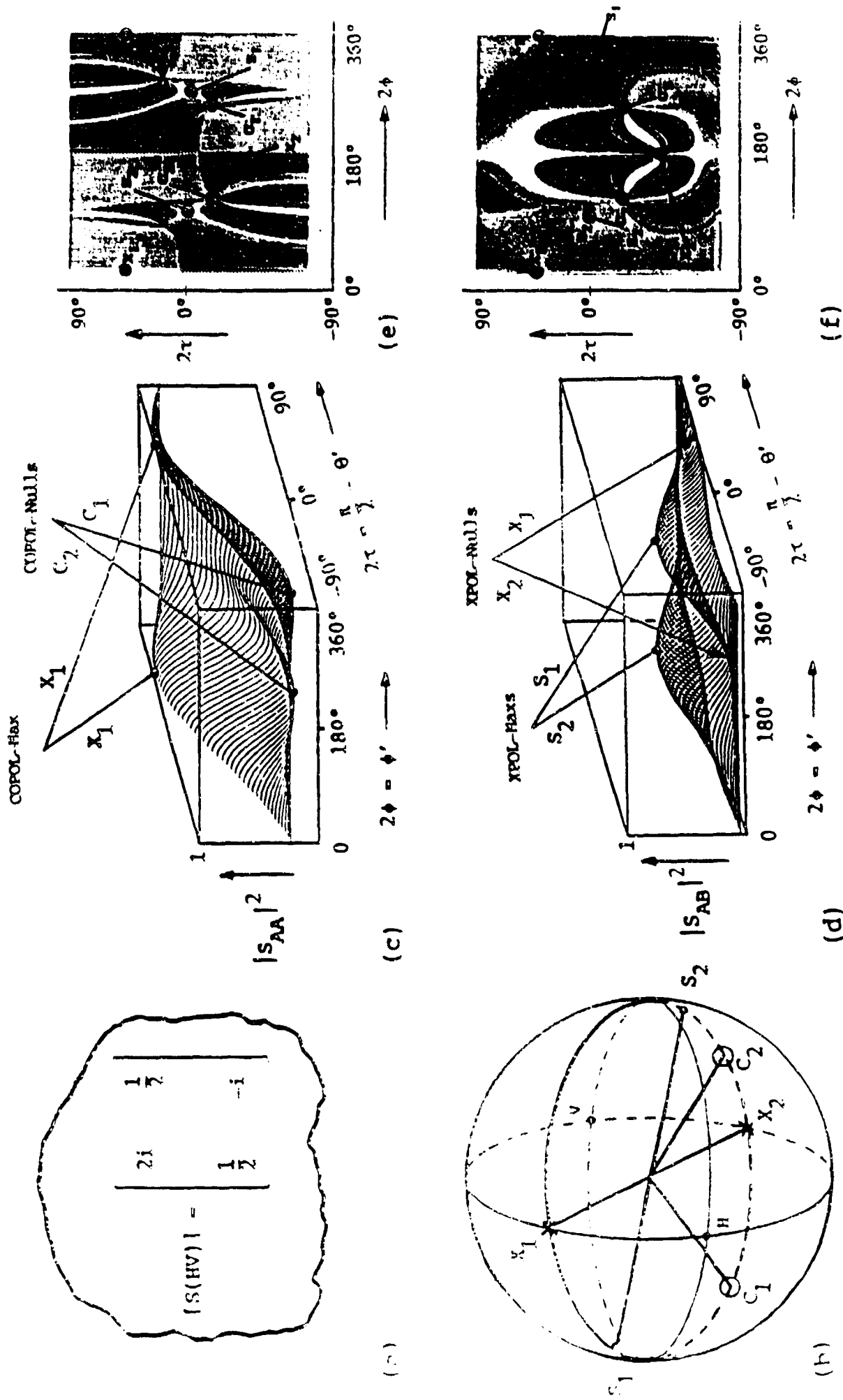


Fig. 3: A General Example

(a) Target Shape
(b) Polarization Fork

(c) Co-Polarization Spectrum
(d) Cross-Polarization Spectrum

(e) Relative Co-Polarization Phase $\phi(\phi, \tau)$
(f) Relative Cross-Polarization Phase $\chi(\phi, \tau)$

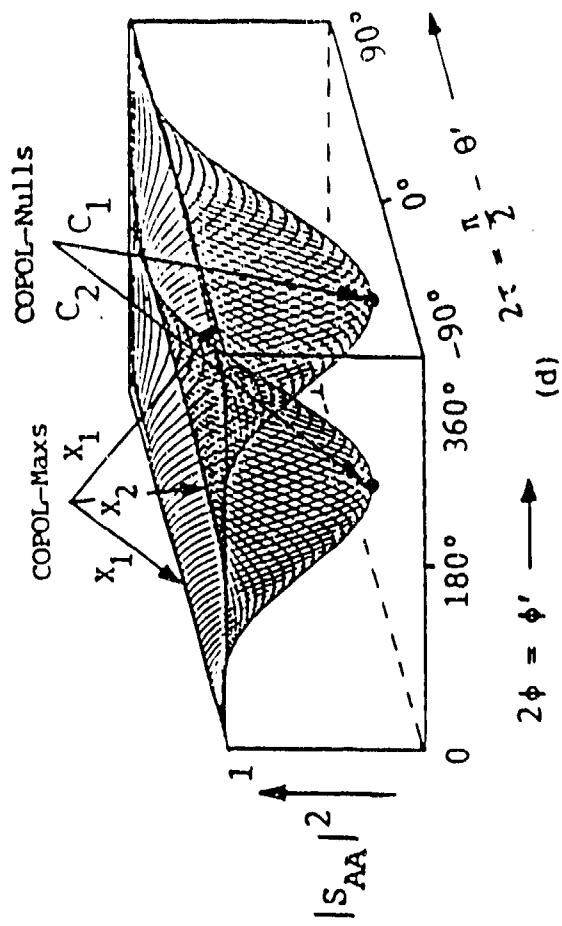
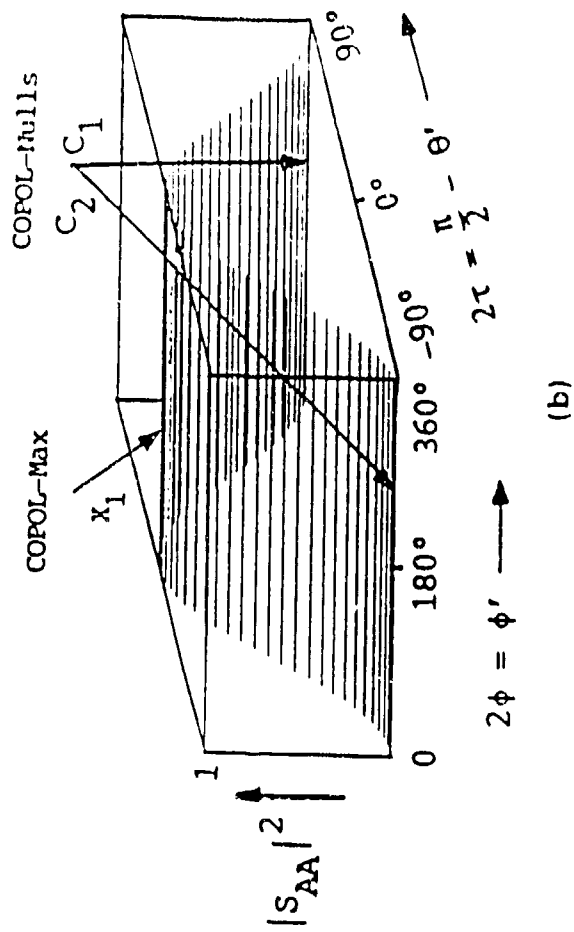
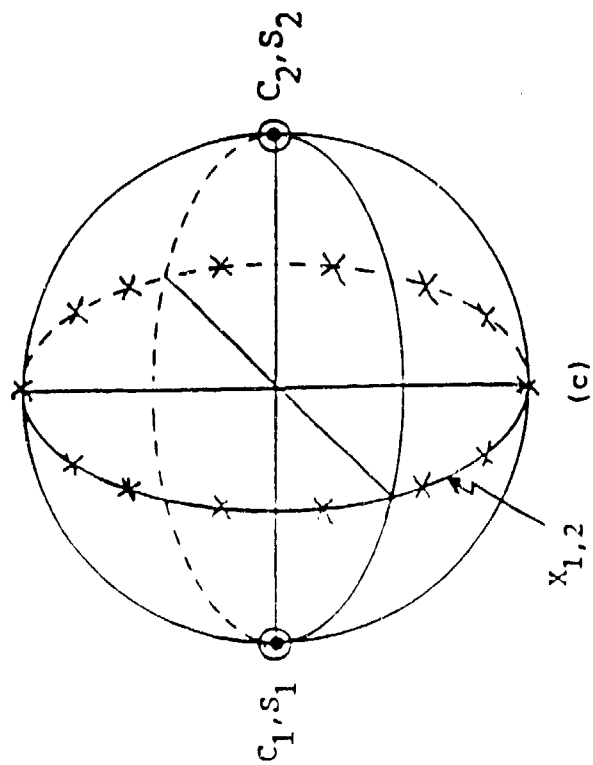
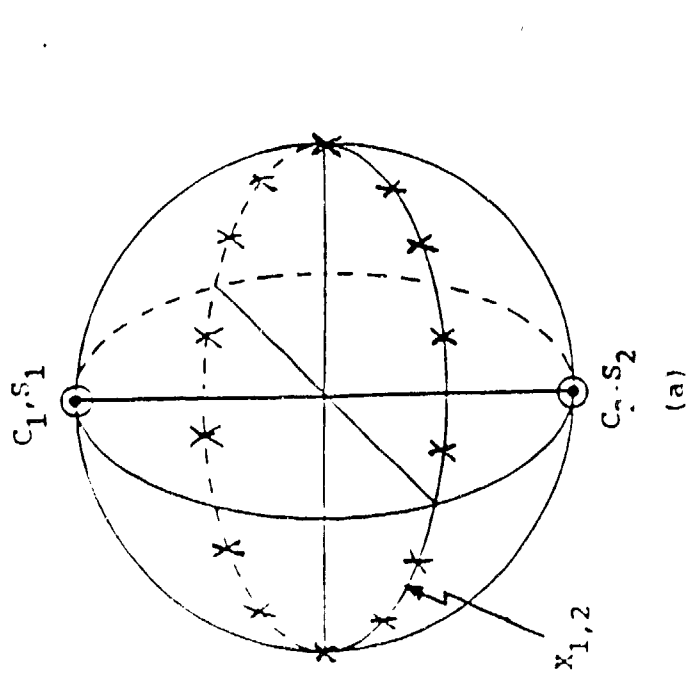


Fig. 4: Flat Plate: (a) Polarization Poincaré Sphere, (b) Co-Polarization Power Spectrum
 Corner Reflector: (c) Polarization Poincaré Sphere, (d) Co-Polarization Power Spectrum

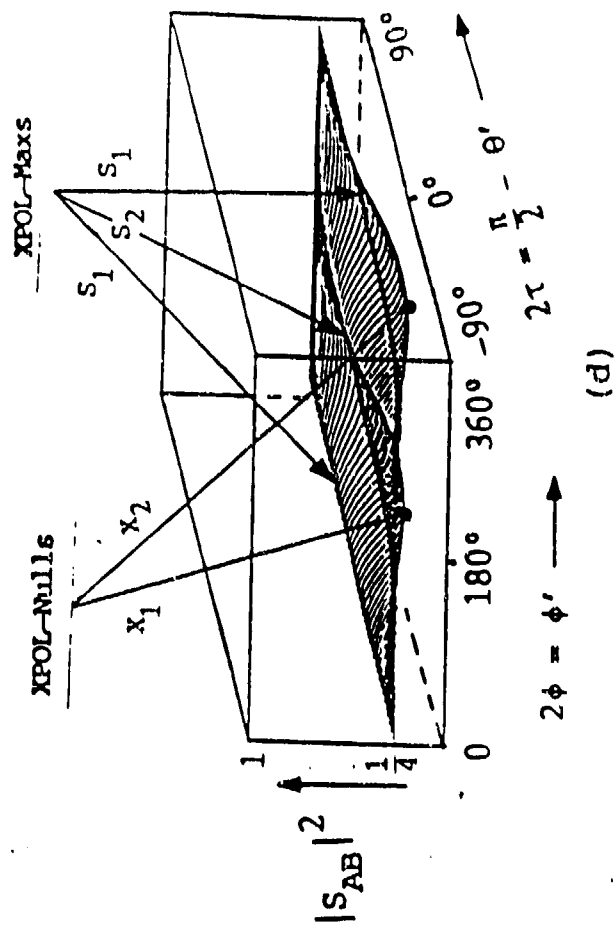
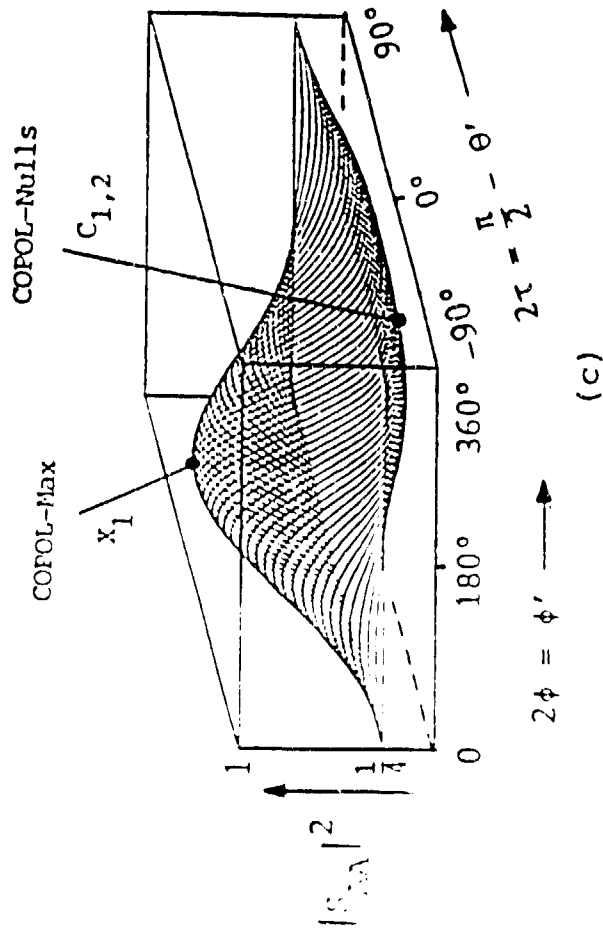
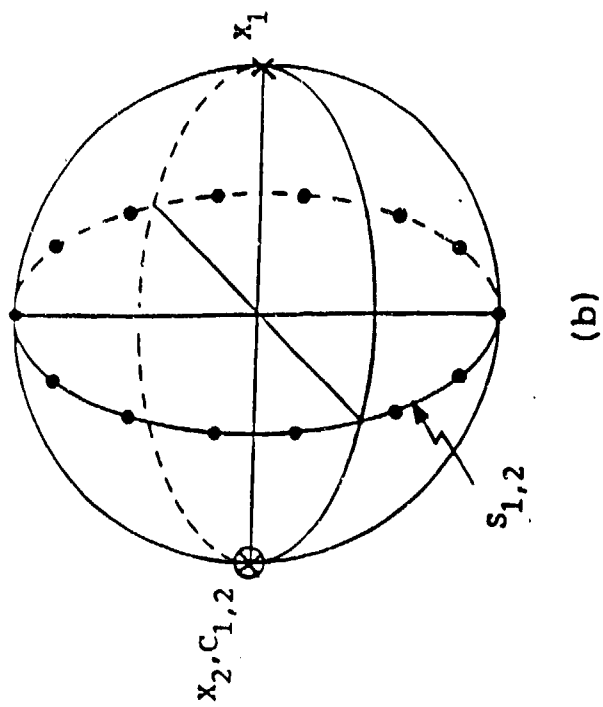
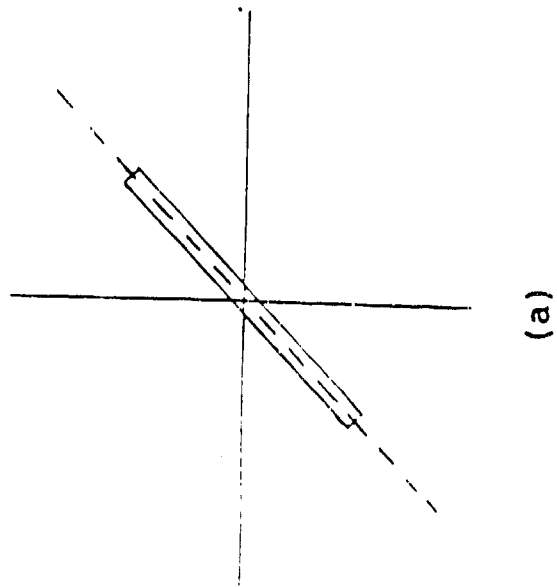
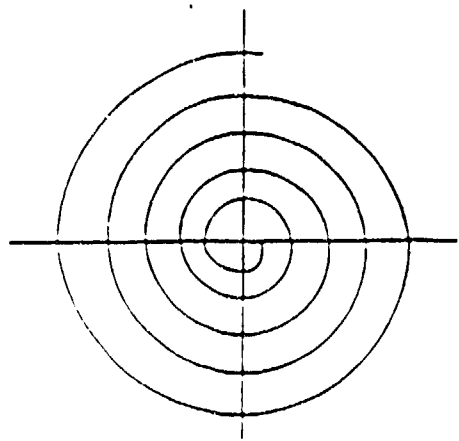
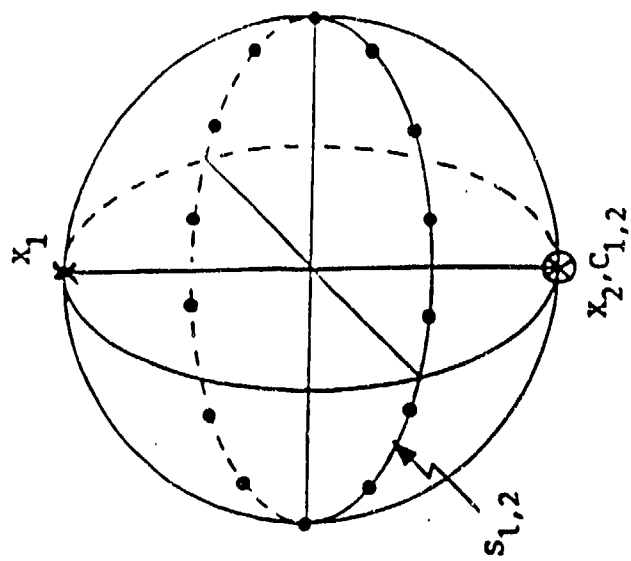


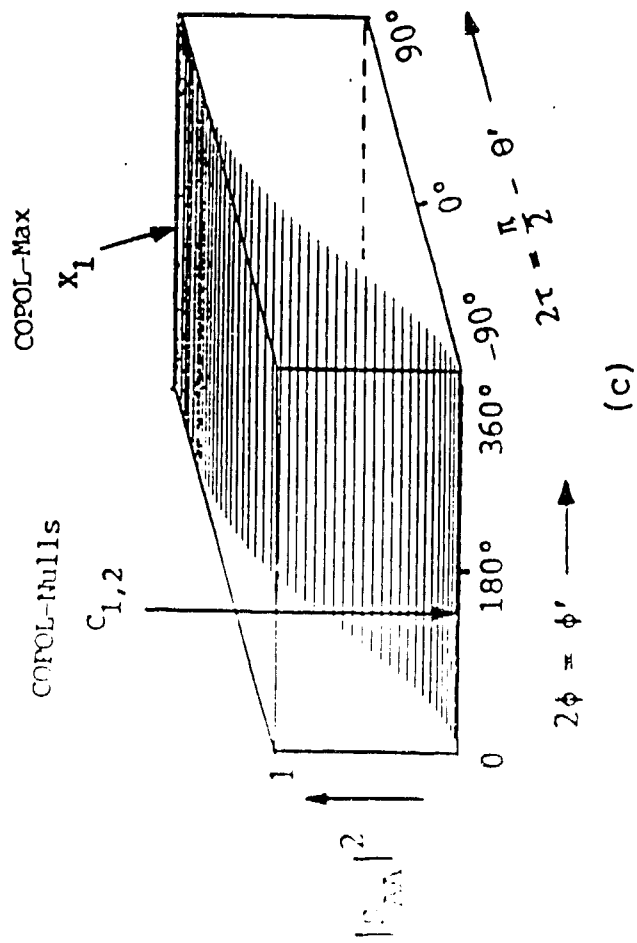
Fig. 5: A 45° Oriented Dipole (a) Target Shape (b) Polarization Fork
(c) Co-Polarization Spectrum, and (d) Cross-Polarization Spectrum



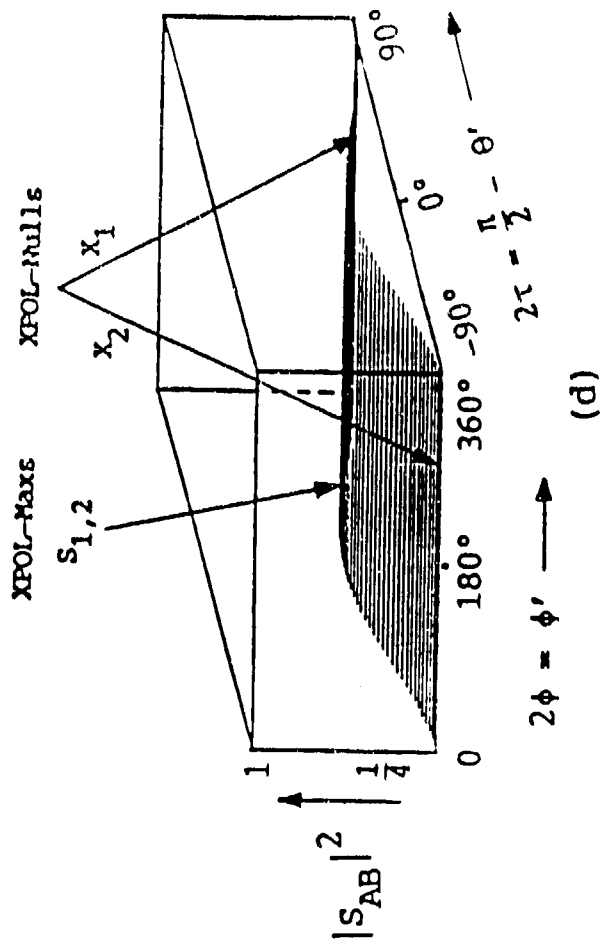
(a)



(b)

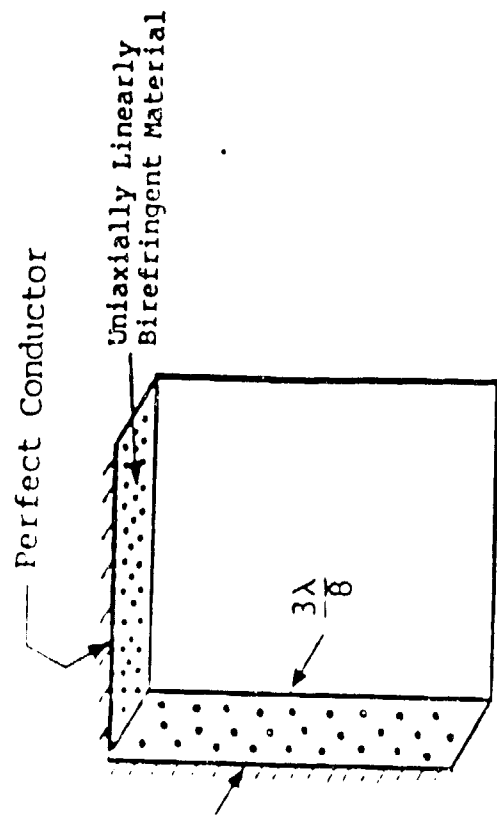


(c)

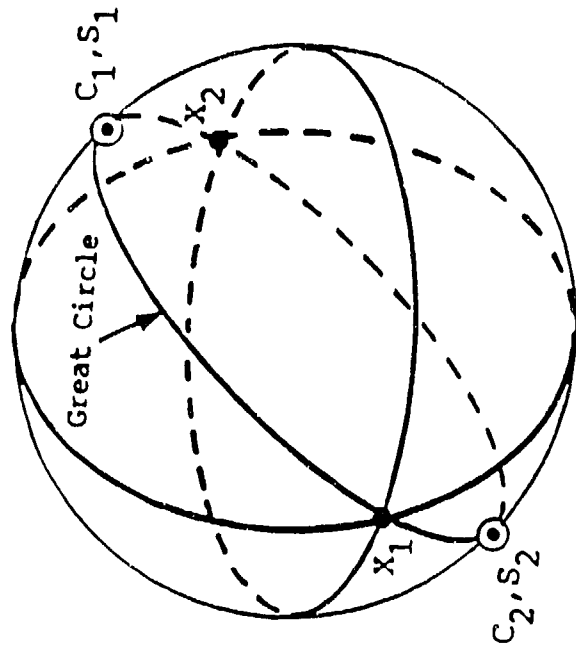


(d)

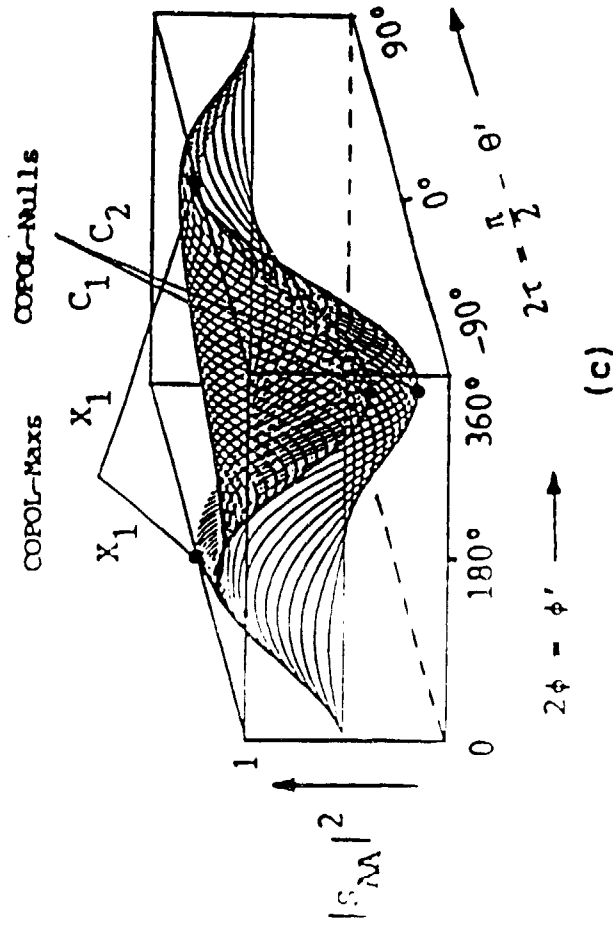
Fig. 6: A Helix with Right Screw (a) Target Shape (b) Polarization Fork (c) Co-Polarization Spectrum, and (d) Cross-Polarization Spectrum



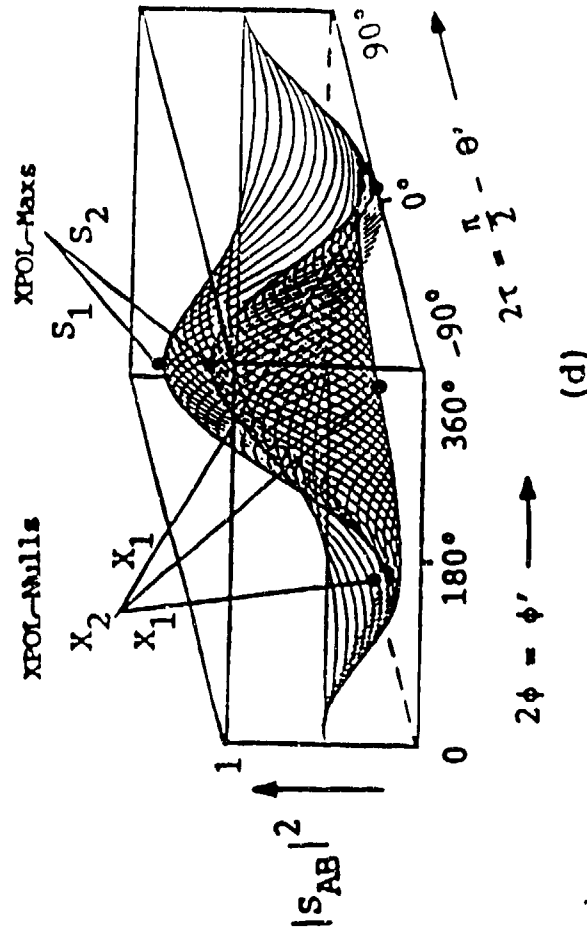
(a)



(b)



(c)



(d)

Fig. 7: A Quarter-Wave Reflector with 90° Phase

(a) Target Shape (b) Polarization Fork (c) Co-Polarization Spectrum (d) Cross-Polarization Spectrum

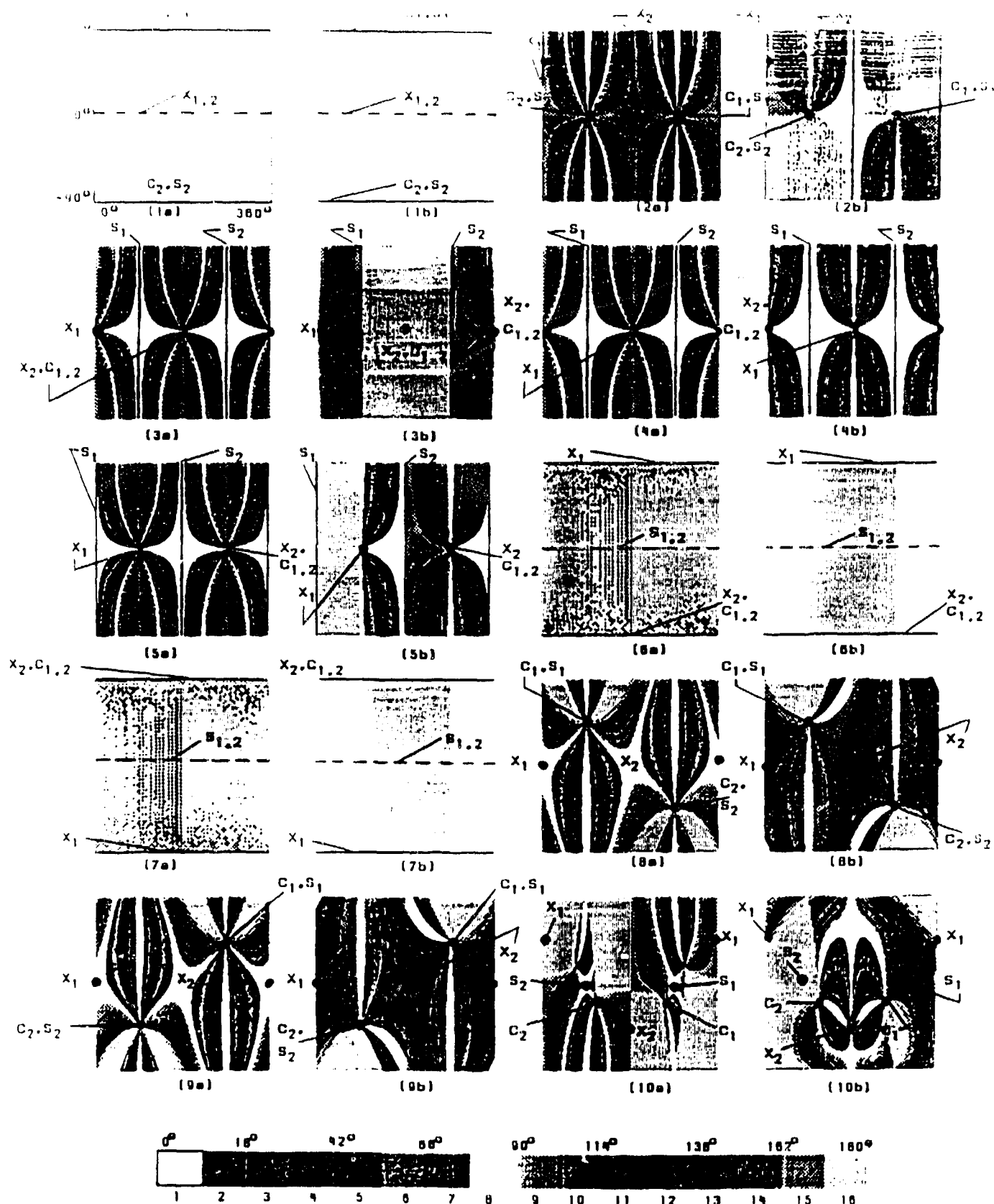


Fig. 8: Relative Co-/Cross-Polarization Phase Plots of the following Targets (where 'a' and 'b' represent the relative Co-Polarization and Cross-Polarization Phase Plots, respectively): (1) A Metallic Sphere or Flat Plate (1a,b); (2) A Dihedral Metallic Corner Reflector (2a,b); (3) A Horizontal Dipole (3a,b); (4) A Vertical Dipole (4a,b); (5) A 45° Oriented Dipole (5a,b); (6) A Helix with Right Screw (6a,b); (7) A Helix with Left Screw (7a,b); (8) A Quarter-wave Reflector with 90° Phase (8a,b); (9) A Quarter-wave Reflector with -90° Phase (9a,b); and (10) A General Example (10a,b)

POLARIMETRIC MATCHED FILTER FOR COHERENT IMAGING

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ABSTRACT

In this paper we focus on image contrast optimization between two rough surface classes. Our approach is based strictly on polarimetric filtering and, therefore, no digital image processing techniques are employed. The approach is tested on a complete polarimetric synthetic aperture radar image of the San Francisco Bay area. The data was taken with the NASA/JPL CV-990 L-band POL-SAR system, where eight real numbers (complex elements of 2×2 polarization scattering matrix) are associated with each image pixel. Optimal transmitted polarizations (corresponding to maxima or minima of reflected energy) are found for each image pixel and the results are analyzed statistically via a set of joint 2D histograms. This is done for both of the rough surface classes. The image response to the "optimal" incident polarization is then simulated digitally by adjusting the receiver polarization according to the modes of the histograms. The corresponding images are computed and displayed with significant image contrast improvement.

I. INTRODUCTION

This paper addresses the problem of coherent image contrast optimization between two rough surface classes. We focus on such contrast which is due to the differences in polarimetric scattering from one rough surface to another. The novelty of this problem is due to the combination of coherent imaging and polarimetric scattering. The former introduces speckle reduction as a major issue while the latter provides the full scattering matrix (i.e., complete polarization information) per image pixel. The second and equally important task of this work is to develop efficient statistical tools for polarimetric image data analysis and speckle reduction techniques.

Speckle has long been recognized as the main problem of coherent imaging (1) and many processing techniques have been advanced to overcome it. The vast majority of these techniques, however, are of a scalar nature simply because vector/matrix imaging data are so sparse and have become available only very recently. Such data, taken with the NASA/JPL CV-990 dual-polarization L-band (1.225 GHz) SAR (Synthetic Aperture Radar) system, have been made available to us. Here, we investigate the potential of a strictly polarimetric image filtering which takes full advantage of the matrix data provided

on a pixel by pixel basis, and complements the existing scalar contrast optimization and speckle reduction techniques. We wish to stress from the outset that our goal is contrast optimization (with the corresponding speckle reduction) without the help of incoherent averaging over pixels or "looks", because of the corresponding loss of spatial or temporal resolution. At first glance, speckle reduction is impossible without incoherent averaging but further consideration shows that it is so only for scalar data. Indeed, taking "projections" onto the receiver direction in the polarization space decreases amplitude fluctuations and an image appears less speckled. The goal of this paper is to find such a choice of the polarization projection which makes a given rough surface class least speckled and, by doing so, to improve the image contrast between two given classes.

The paper is structured as follows: a brief description of basic polarimetric definitions is provided in Section II, while in Section III the image data are described and the precise problem formulation is given. In Section IV, our three-stage polarimetric optimization procedure is outlined and implemented for each image pixel. In Section V, we make the transition from the single pixel result to a combined description. A

statistical analysis of the results is given, and the images are displayed and discussed. The operation of the polarimetric matched filter is summarized in Section VI. Section VII contains concluding remarks.

II. ESSENTIAL POLARIMETRIC DEFINITIONS

Following (2), we define the origin of the coordinate system at the receiving antenna terminals with the z -axis directed toward the target (pixel) as shown in Fig. 1. Note that in SAR applications the receiver and transmitter are co-located but may be different antennas so that the situation is slightly bistatic. The reflected \underline{E}_R and the transmitted \underline{E}_T waves, together with the antenna "height" \underline{h} (polarization of the receiving antenna when used as transmitter (2)), can all be written as plane waves

$$[1a] \quad \vec{E}_T = (E_{T1}^2 + E_{T2}^2)^{1/2} [\cos \gamma_T \hat{x} + \sin \gamma_T e^{j\phi_T} \hat{y}] \cdot \exp \{j(\omega t - kz + \alpha_T)\}$$

$$[1b] \quad \vec{E}_R = (E_{Rx}^2 + E_{Ry}^2)^{1/2} [\cos \gamma_R \hat{x} + \sin \gamma_R e^{j\phi_R} \hat{y}] \cdot \exp \{j(\omega t + kz + \alpha_R)\}$$

$$[1c] \quad \vec{h} = (h_x^2 + h_y^2)^{1/2} [\cos \gamma_h \hat{x} + \sin \gamma_h e^{j\phi_h} \hat{y}] \cdot \exp \{j(\omega t - kz + \alpha_h)\}$$

where in all equations $\gamma = \tan^{-1}(E_Y/E_X)$, and ϕ and α are the relative and absolute phases, respectively (2). From here on, we will operate with the expressions in square brackets, written as complex normalized 2D vectors (also known as Jones vectors (3) in optics and spinors in quantum mechanics (4)), e.g.,

$$\underline{E}_T = \begin{bmatrix} \cos \gamma_T \\ \sin \gamma_T e^{j\phi_T} \end{bmatrix} = \begin{bmatrix} E_H \\ E_V \end{bmatrix}_T$$

When usual assumptions about a linear passive medium are employed, the input-output polarization ellipse characteristics of a target (image pixel) are given by its scattering matrix defined as

$$[2] \quad \underline{E}_R = [S]\underline{E}_T$$

where $[S]$ is a 2 x 2 complex matrix, and α_T is set to zero by the choice of the time origin (2). Finally, the voltage at the receiving antenna terminals as a function of transmitter and receiver polarizations is given by

$$[3] \quad V = \underline{h}^T \underline{E}_R = \underline{h}^T [S] \underline{E}_T$$

where superscript T denotes the transpose (as opposed to hermitian conjugate - see (2, pp. 1471-1473), and (5) for

details). For reference, we also include the transformation properties of $[S]$ and V from one polarization basis to another using a similarity transformation for $[S]$ to $[S]'$ as discussed in (2, pp. 1471-1473),

$$[4a] \quad [S]' = [U]^{-1}[S][U]$$

$$[4b] \quad V' = V = \underline{h}'^T [U]^T [U] \underline{E}_R' = \underline{h}^T \underline{E}_R$$

where $[U]$ is the unitary change-of-basis matrix and primes indicate quantities in the new basis. With these definitions we now proceed to describe the polarimetric SAR image data and to formulate the problem more precisely.

III. IMAGE DATA DESCRIPTION AND PROBLEM FORMULATION

The 4096 x 1024 SAR image of the San Francisco Bay area (6,7) is shown in Fig. 2a for horizontal transmitter and receiver polarizations (HH). The brightness of each pixel is assigned according to the total received energy in the horizontal channel. The data was taken with a dual-polarized antenna and a four-channel receiver system so that a complete scattering matrix was measured for each image pixel. The radar wavelength was 24.5 cm and the resolution (size of each pixel size) was about 10m x 10m (see (6) for more details). The image

texture can be roughly classified into three main categories: man-made structures (ships, the bridge, urban area, etc.), vegetated area (park), and the ocean region. All three classes can be considered rough at 24.5 cm according to the Rayleigh criterion (1). This surface roughness leads to a random modulation of phase of the reflected wave which, in turn, produces image speckle (1).

Any kind of averaging is likely to smoothen the image and reduce speckle. As an example of averaging in polarization space, the span of [S] image (sum of the magnitudes of all four scattering matrix elements) is shown on Fig. 2b. The image is essentially an incoherent superposition of the four separate polarization images obtained per pixel and, therefore, a noticeable speckle reduction (relative to the HH image) is not surprising (8). As was mentioned above, this paper focuses on contrast optimization without incoherent averaging of any kind.

Since a complete scattering matrix is available for every pixel of each of the three categories, one can simulate the response of the area to any transmitted polarization \underline{E}_T by calculating \underline{E}_R via [2]. Furthermore, the response of the image can also be simulated for an arbitrary receiver polarization \underline{h} via [3]. Both equations must be implemented for each pixel of

the entire image. The brightness is then assigned to each pixel according to $P = V^* V = (h^T E_R)^* (h^T E_R)$ (* stands for complex conjugate). Such numerical simulations were recently carried out by the JPL group (6,7), demonstrating the ability of polarimetric adjustment to substantially improve image contrast. Our goal here is to develop an algorithm for the search of optimal image contrast via the combination of our recently developed Three-Stage-Procedure (TSP) which is described in the following section, and a subsequent statistical analysis of the set of polarization eigenvectors computed with the TSP for each pixel. Again, we emphasize that our algorithm must not include any incoherent averaging and/or smoothing procedures because of the corresponding loss of information, e.g., temporal (phase) or spatial resolution. In this paper we focus on finding such transmitter and receiver polarizations that allow significant ocean clutter removal for better contrast with the urban area and ship/man-made structure identification. The method and implementation of the optimal polarization search for a single pixel are briefly described in the next section, after which we proceed to the statistical analysis of the results.

IV. THE THREE-STAGE PROCEDURE

The TSP addresses the following problem (see (2,5) for more details): For a given pixel (i.e., known scattering matrix), find such transmitting and receiving polarizations, for which the received power is maximal (minimal). In mathematical terms this means: find \underline{E}_T and \underline{h} such that $P = \underline{V}^* \underline{V} = |\underline{h}^T(S)\underline{E}_T|^2$ is optimal for a given $[S]$, subject to the constraints $||\underline{h}|| = ||\underline{E}_T|| = 1$.

The TSP accomplishes this in three separate stages (2):

Stage 1) The energy density in the reflected wave (before it has reached the receiver) is optimized as a function of transmitted polarizations via the following eigenvalue problem

$$[5] \quad ([G] - \lambda[I])\underline{E}_{T,opt} = 0$$

where $[G] = [S]^+ [S]$ is by construction a hermitian matrix for any $[S]$ (+ stands for hermitian conjugate), $[I]$ is the identity matrix, and $\underline{E}_{T,opt}$ is the eigenvector corresponding to the largest (smallest) eigenvalue λ_{max} (λ_{min}) giving the largest (smallest) energy density. The eigenvalues are always real (they correspond to the measured values of energy density in the reflected wave) and the eigenvectors

are orthogonal because $[G]$ is hermitian (9).

Stage 2) At this stage, the polarization state of the reflected wave is computed using the known $\underline{E}_{T,opt}$

$$[6] \quad \underline{E}_{R,opt} = [S]\underline{E}_{T,opt}.$$

Stage 3) Finally, the receiver polarization is adjusted to ensure that all of the power contained in $\underline{E}_{R,opt}$ (reflected wave) is either absorbed or rejected, depending on the application. The former is accomplished with the choice

$$[7a] \quad \underline{h} = \underline{E}_R^*$$

while the latter requires that

$$[7b] \quad v = \underline{h}^T \underline{E}_R = 0.$$

In terms of imaging applications, one expects a given pixel to look relatively "bright" when \underline{E}_T corresponds to the largest eigenvalue (maximal energy density) and \underline{h} is adjusted according to [7a], while the adjustment [7b] ensures that the pixel looks "dark", especially when supplemented with the choice of minimal $\underline{E}_{T,opt}$. These observations, together with the statistical considerations, constitute the basis of pixel-by-pixel polarimetric image filtering.

V. STATISTICAL ANALYSIS OF OPTIMAL POLARIZATIONS AND IMAGING

Even within a single rough surface class (e.g. ocean), there is a considerable variability in polarization properties of pixels in any given patch and we, therefore, must introduce a statistical description at this stage. We assume that the two terrain classes are sufficiently different in their polarimetric responses so that their statistics do not "overlap" significantly. Then, with proper statistical tools, a "threshold" can be found such that the TSP can be used to "darken" not just one pixel but a majority of pixels in a given class.

In order to gain insight into the polarimetric response of various terrain and ocean categories, we have performed Stage 1 of the TSP for each pixel of two chosen segments of ocean and urban areas. Let us consider the ocean vs. city contrast enhancement as a specific application. In order to minimize the ocean return or to maximize the city return, the minimum energy eigenvector is computed for each pixel of the ocean patch and the maximum energy eigenvector is computed for the city patch. The eigenvectors corresponding to λ_{\min} , λ_{\max} are computed according to [5] for each pixel and expressed in the form (2, p. 1400)

$$[8a] \quad E_{T,opt} = \frac{1}{\sqrt{(1 + \rho\rho^*)}} \begin{bmatrix} 1 \\ \rho \end{bmatrix}, \quad \rho = E_Y/E_X$$

where ρ is the complex polarization ratio (3). After the eigenvectors are computed, we express them in terms of the more convenient ellipticity ϵ and tilt τ coordinates which describe, respectively, the "fatness" and the inclination of the polarization ellipse. They are defined (3, p. 35) as

$$[8b] \quad \epsilon = 1/2 \arcsin\{2\text{Im}(\rho)/(1-\rho\rho^*)\}$$

$$[8c] \quad \tau = 1/2 \arctan\{2\text{Re}(\rho)/(1-\rho\rho^*)\}$$

Thus, an optimal polarization state which makes a given pixel darkest (brightest) is characterized by two numbers, ϵ and τ . Naturally, one would like to choose the incident polarization in such a way as to make most ocean pixels dark if our goal is to contrast urban area against ocean or to enhance visibility of ships at sea. To this end, we present in Figs. 3a-b joint 2D histograms (ϵ and τ) for the two surface categories of interest: statistics of minimal eigenvectors are presented for the ocean, and maximal eigenvectors for the urban area. Each patch contains 40,000 (200 X 200) pixels so that the statistics are quite good. Both histogram modes are near the linear vertical

($\epsilon \approx 0^\circ$, $\tau \approx 90^\circ$) polarization. Thus, if the transmitter is adjusted to produce vertically polarized waves (relative to the direction of propagation), the majority of the ocean pixels will have relatively low scattered energy, while the majority of city pixels will reflect strongly. Once the optimal transmitted field is chosen and the scattered field is computed, one can use a similar procedure for the receiver adjustment. In Figs. 4a-b, we present the ϵ - τ histograms for the scattered fields of the two regions. These histograms were constructed by letting the incident wave be vertically polarized and by computing the scattered field of each pixel via Eq. 6. Again, the two histograms peak around the same vertical polarization state and the ocean distribution is more pronounced. In fact, the ocean incident and scattered field histograms are quite similar which leads one to conclude that most of the scattering matrices of the ocean region are "flat plate-like" identity matrices. This behaviour is consistent with Bragg scattering assumed to be the dominant physical mechanism of the ocean scattering (6). The urban area histograms, on the other hand, differ because the scattered field does not have a peak at horizontal polarization. The fact that this peak vanishes seems to disagree with the assumption of dihedral corner reflectors (6) as the basic

scattering elements of the urban area. Indeed, in such a case, the scattering matrix (having entries ± 1 along the diagonal and 0 along the off-diagonal) would produce a mild peak at horizontal polarizations which would not disappear.

If the receiver is adjusted to horizontal polarization, most of the energy of ocean pixels will be rejected because the receiver is perpendicular to the sharp histogram mode at vertical polarization. The urban area will not be affected as much because of the much larger spread. When the brightness is assigned according to $P = V^*V$ (V is computed from Eq. 3), the image in Fig. 5a results. Compared with the original HH image, this near HV image has better contrast: the average brightness ratio between the urban and the ocean areas increases; but, because of the fact that the two modes are not separated in the polarization space, the urban area has lost some structure. Note, however, that most of the ocean speckle has been "filtered out" with the proper choice of polarization, yet, without significant effect on the man-made structures.

The image of Fig. 5b was computed for the vertical polarization of the receiver (near VV image). The ocean area is quite a bit more speckled than on Fig. 5a and the contrast with the urban area is lower. On the other hand, there is a better

contrast between park/vegetated area and the urban region. Thus, the results of the JPL group (6) as well as our experiments clearly show that a much improved contrast can be achieved between man-made, vegetated and ocean areas with the proper choice of polarization. Of course, when the rough surface is such that the scattering is polarimetrically isotropic (i.e., there is no spatial polarization dependence), this technique cannot work (one such example is a random sea surface). Fortunately, such cases are rather unlikely and all of the data available to us indicate that real terrestrial rough surfaces exhibit a very strong polarization dependence. Even an ocean surface is often modulated by well-defined internal wave patterns which show up clearly in POL-SAR images.

A sequence of one-dimensional image brightness distributions in Fig.6 illustrates the effect of various steps of the above procedure on the ocean and city patches, separately. One notices a gradual improvement in contrast between the two categories as indicated by the decreasing overlap area and better peak separation. This suggests that the h-adjustment is responsible for most of the clutter removal, as can also be seen on the actual images of Figs. 5a and 5b. Note that identical uniform grey scale assignments have been used for all images so

that the effects are entirely polarimetric.

VI. SUMMARY OF THE POLARIMETRIC MATCHED FILTER STRATEGY

In this section, we summarize and quantify the approach outlined in the previous paper in a series of well-defined steps. Again, consider the suppression of ocean clutter for optimal contrast with man-made structures such as ships, etc. We perform the first two steps of the TSP, and display the "typical" statistics of the ocean and urban area patches in a form of joint bivariate histograms of transmitted \underline{E}_T and received \underline{E}_R fields as is shown in Figs. 3a,b and 4a,b. We then identify the modes of the two distributions \underline{E}_T and \underline{E}_R and adjust \underline{h} so that the "majority" (i.e., histogram peak) of the "unwanted" patch pixels "darken". For instance, if \underline{h} is adjusted in such a way that the peak in the ocean distribution \underline{E}_R satisfies

$$[9] \quad V_{\text{peak}} = \underline{h}^T \underline{E}_{R,\text{peak}} = 0,$$

it is ensured that the majority of the ocean pixels will appear "black" on the actual image.

The following procedure (see Fig. 7), which is a statistical extension of the TSP, constitutes the polarimetric matched

filter for coherent imaging:

- 1a) the energy density of each pixel is maximized (minimized) as a function of the transmitted polarization. The corresponding eigenvectors, \underline{E}_T , are found from Eq. 5 as in Stage 1 of TSP;
- 1b) the joint bivariate histograms of \underline{E}_T (ϵ and τ) are constructed for all rough surface classes of interest;
- 1c) the transmitted field \underline{E}_T is adjusted to either the peak of the minimal eigenvector pdf of the unwanted region (e.g., to reject ocean clutter) or to the peak of the maximal eigenvector pdf of the region of interest (e.g., bridge, urban area, etc.). The choice depends on the relative sharpness of the modes;

- 2a) the scattered field \underline{E}_R is computed for each pixel for the \underline{E}_T chosen in Step 1c, see Eq. 6 in Stage 2 of TSP;
- 2b) as in Step 1b, the joint (ϵ and τ) histograms of the scattered field \underline{E}_R are constructed. The histogram mode is identified.

- 3a) the receiver polarization \underline{h} is adjusted via Eqns. 7a or 7b to either match or mismatch the polarization of the histogram mode found in Step 2b;

3b) $P = \underline{V}^* \underline{V}$ (received power) is computed for each pixel as
 $P = (\underline{h}^T \underline{E}_R)^* (\underline{h}^T \underline{E}_R) = (\underline{h}^T [S] \underline{E}_T)^* (\underline{h}^T [S] \underline{E}_T)$, and the resulting
 image is displayed.

VII. CONCLUDING REMARKS

The potential of complete polarimetric methods for radar imaging has already been convincingly demonstrated by the JPL group (6,7). In this paper, we have attempted to quantify and organize a search for optimal image contrast into a systematic polarimetric filtering method. In addition, no incoherent pixel/look or spatial averaging was allowed. We have accomplished this by combining the TSP search for optimal polarizations on a pixel-by-pixel basis with a subsequent statistical analysis of polarization eigenvectors (versus surface category), and the digital adjustment of the polarimetric variables \underline{E}_T and \underline{h} . We find the preliminary results (Figs. 3-7) promising.

The effectiveness of our strategy depends sensitively on the sharpness of the relevant histogram peaks because such a sharpness reflects similarity of the polarimetric scattering behaviour of all the pixels within a given class. Therefore, other image processing techniques, when used in conjunction with

the polarimetric enhancement, should be directed towards the increase in peak sharpness of the relevant field distributions (e.g., $N \times N$ block averaging, discretization, and quantization, etc.). Here, however, we concentrate strictly on polarimetric enhancement methods. Furthermore, the polarimetric image contrast improves with the separation of the histograms in the polarization space (two "spikes" with no overlap would correspond to a "black and white" image with an ideal contrast). In this respect, the TSP was not successful because the scattered field histograms of ocean and the urban area (Figs. 4a and 4b) are approximately at the same ϵ and τ . Another approach would be to choose the transmitting field in such a way as to maximize the peak separation of the scattered field histograms. This approach is currently under investigation in our laboratory and preliminary results based on Monte-Carlo simulation of structures in Rayleigh noise indicate better contrast (relative to TSP) but less efficient speckle reduction.

We wish to state here that an immediate objective of the research is to establish a "tool-kit" of matrix image processing techniques, designed specifically for the handling of polarimetric scattering matrix data on a pixel-by-pixel basis. Consequently, we did not emphasize either the modeling or an

interpretation of polarimetric scattering patterns beyond some very basic physical arguments based on flat plates, corner reflectors, Bragg scattering, etc.

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LIST OF FIGURES

Fig. 1. Arrangement of Coordinate System for Polarimetric SAR.

Fig. 2. Synthesized Images: (a) HH Element of $[S]$ and (b) Span of $[S]$.

Speckle in these coherent images is due to random phase modulation associated with surface roughness. The span image (b) has less speckle than the HH image (a) because span

$[S] = |S_{HH}|^2 + |S_{HV}|^2 + |S_{VH}|^2 + |S_{VV}|^2$ is an incoherent average

of four images. Sixteen uniformly spaced gray scale levels have

been used to cover the voltage values in the range $(10^{-3.5}, 10^{-1.5})$

on a logarithmic scale.

Fig. 3. Histogram of Optimal Transmitted Polarizations: (a) Ocean Region and (b) Urban Region.

Optimal eigenvectors were computed for each pixel of the 200×200 ocean and urban regions (see Step 1 of the PMF). These eigenvectors were histogrammed in ellipticity ϵ and tilt τ coordinates (see eq. [8]). Minimum energy eigenvectors were found for ocean pixels and maximum for urban pixels. The mode (peak of the histogram) location indicate that at E_T of $\epsilon = 0^\circ$ and $\tau = 90^\circ$ (vertically polarized), a majority of ocean pixels will respond weakly. Fortunately, the modes of (a) and (b) are the same and, therefore, the majority of city pixels will respond strongly to the same polarization.

Fig. 4. Histogram of Scattered Polarizations: (a) Ocean Region and (b) Urban Region.

The scattered field E_R was computed for each pixel of the 200×200 ocean and urban regions; the transmitted polarization was chosen in accord with Fig. 3. These scattered polarization were histogrammed in ellipticity ϵ and tilt τ coordinates (see Step 2 of the PMF).

The ocean mode at $\epsilon = 0^\circ$ and $\tau = 90^\circ$ indicates that a majority of ocean pixels are mismatched by adjusting h to $\epsilon = 0^\circ$ and $\tau = 0^\circ$.

Because the two modes coincide, an appreciable portion of the urban region will also be mismatched. However, the large spread of the urban histogram still leads to significant contrast improvement.

Fig. 5. Synthesized Images: (a) Ocean Polarization Mismatched and (b) Ocean Polarization Matched.

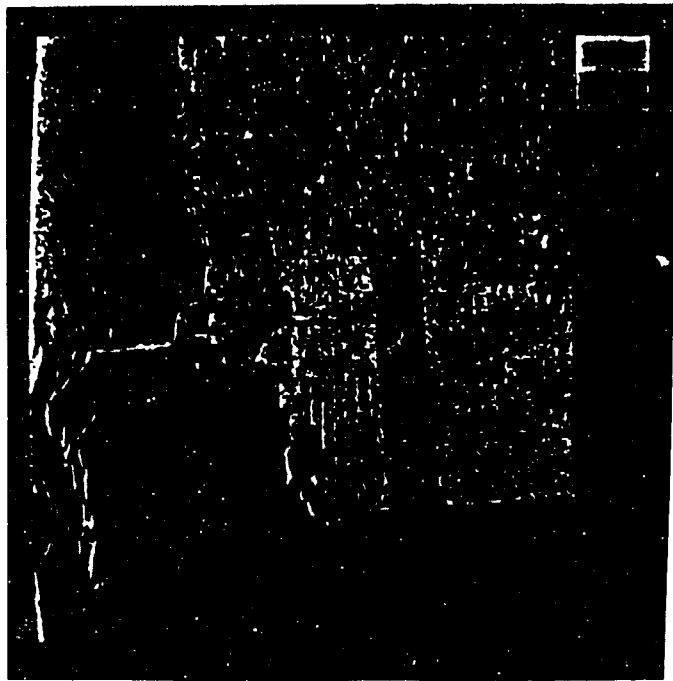
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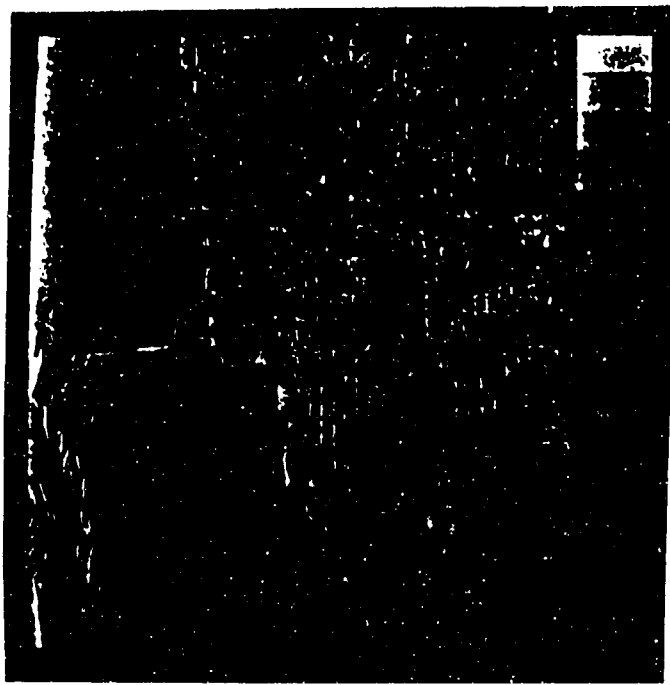
Fig. 6. Effect of PMF on Image Brightness Distributions: (a) HH Reference, (b) Optimal Reflected Energy (see Step 1 of the PMF), (c) Ocean Matched, and (d) Ocean Mismatched (see Step 3 of the PMF).

All voltage values are normalized by the transmitted energy and, therefore, their logarithms are negative. The decrease in relative overlap area between (a) and (d) indicates contrast enhancement. Also, note that the decrease in variance of the ocean distribution between (a) and (d) signifies speckle reduction.

Fig. 7. PMF Flow Chart with Application to Ocean vs. Urban Contrast Enhancement.



(a)



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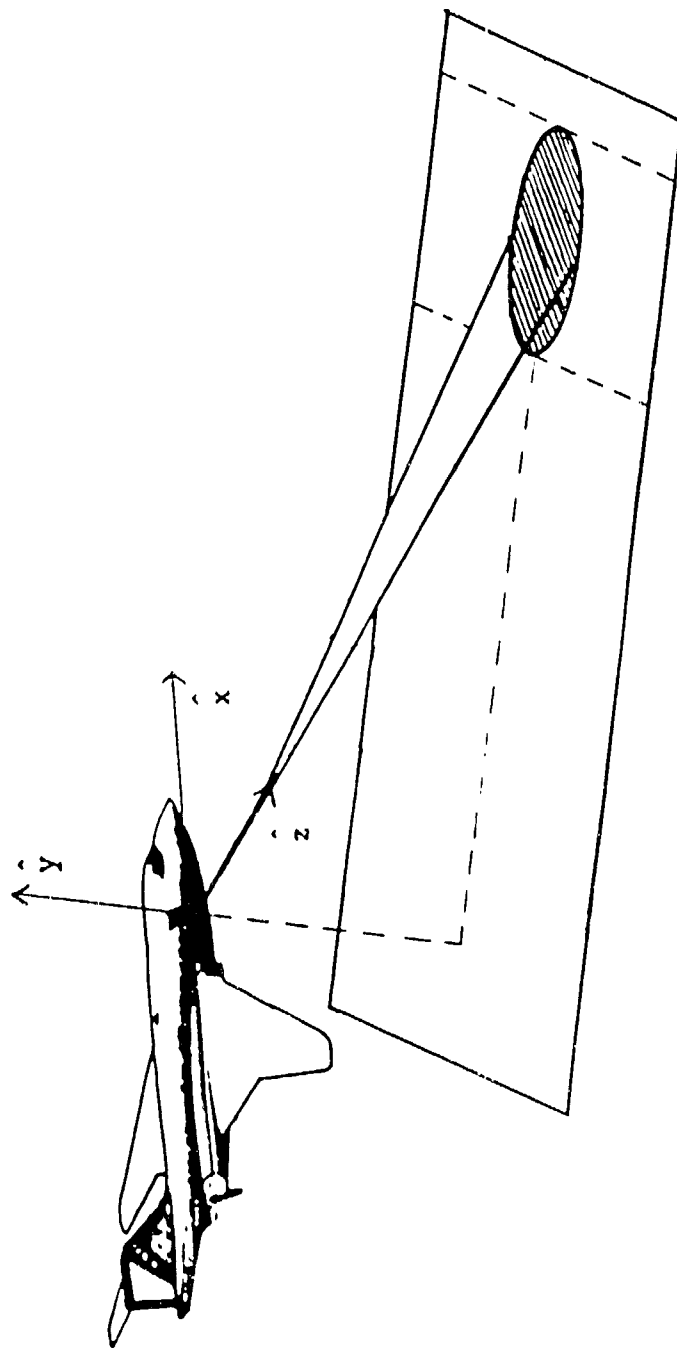


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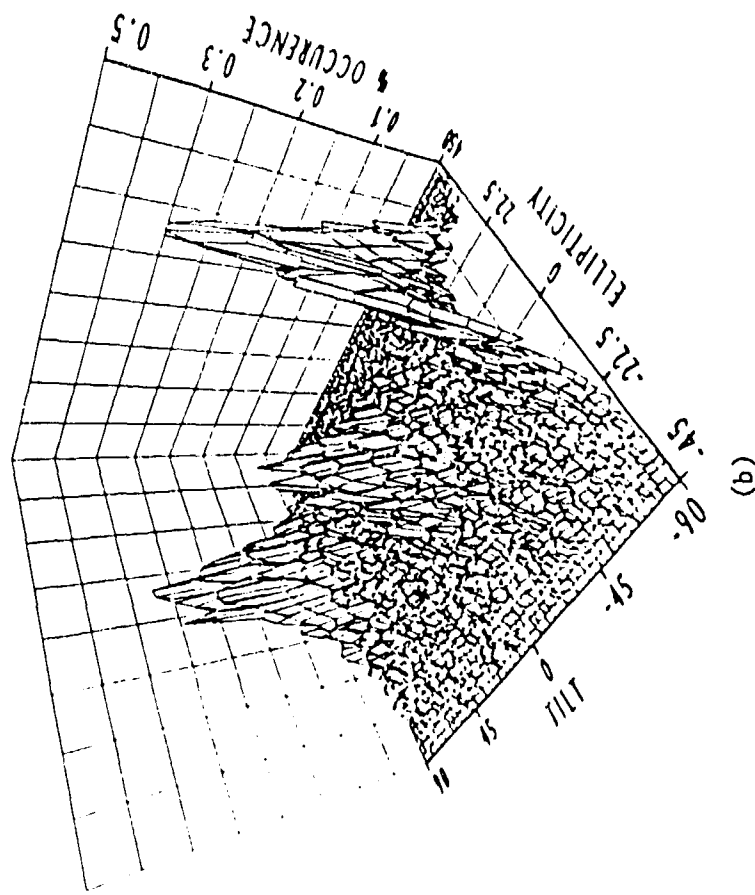
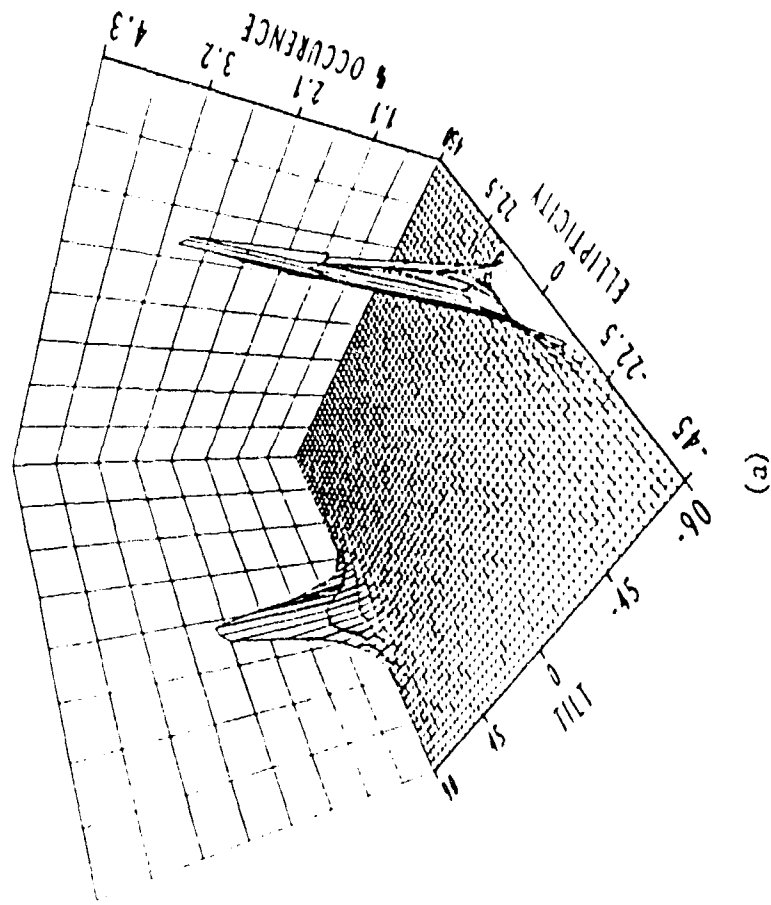


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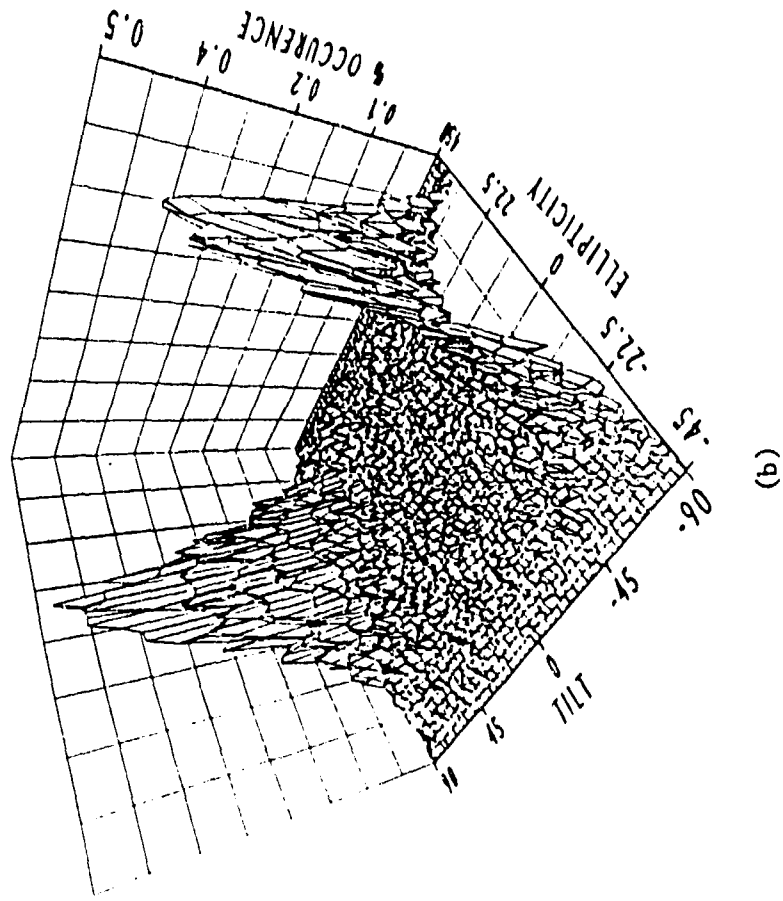
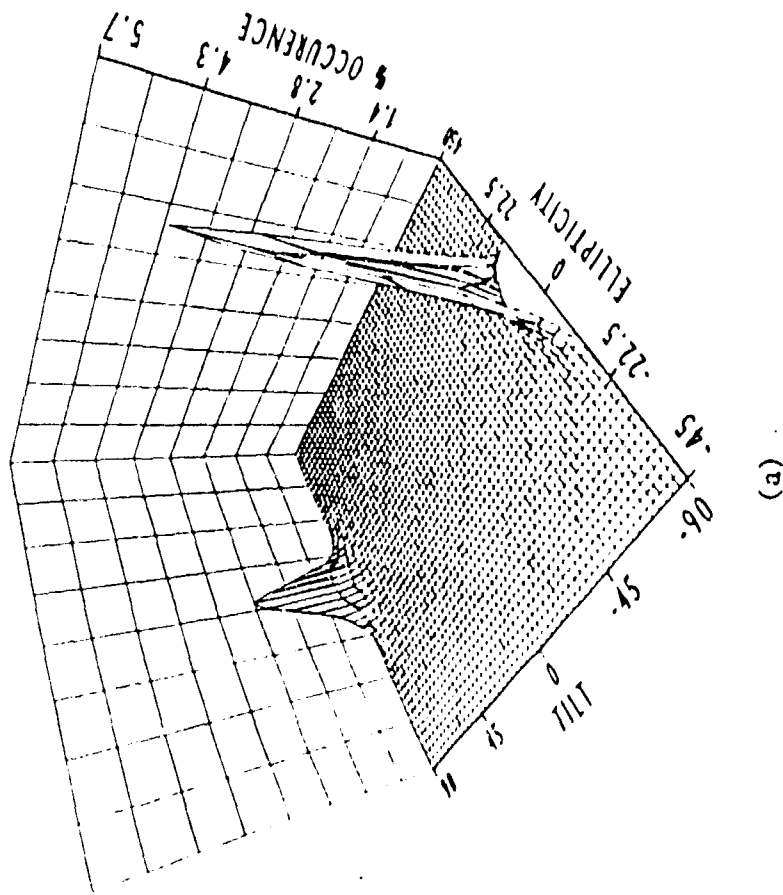
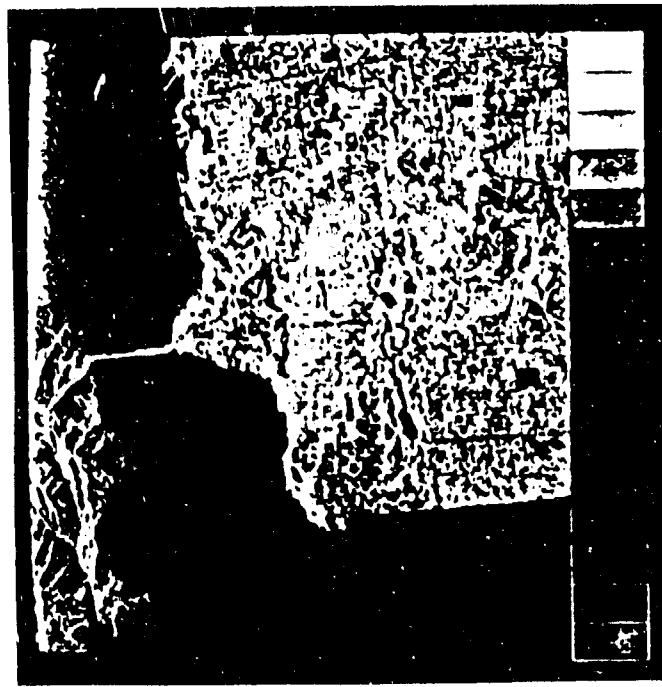


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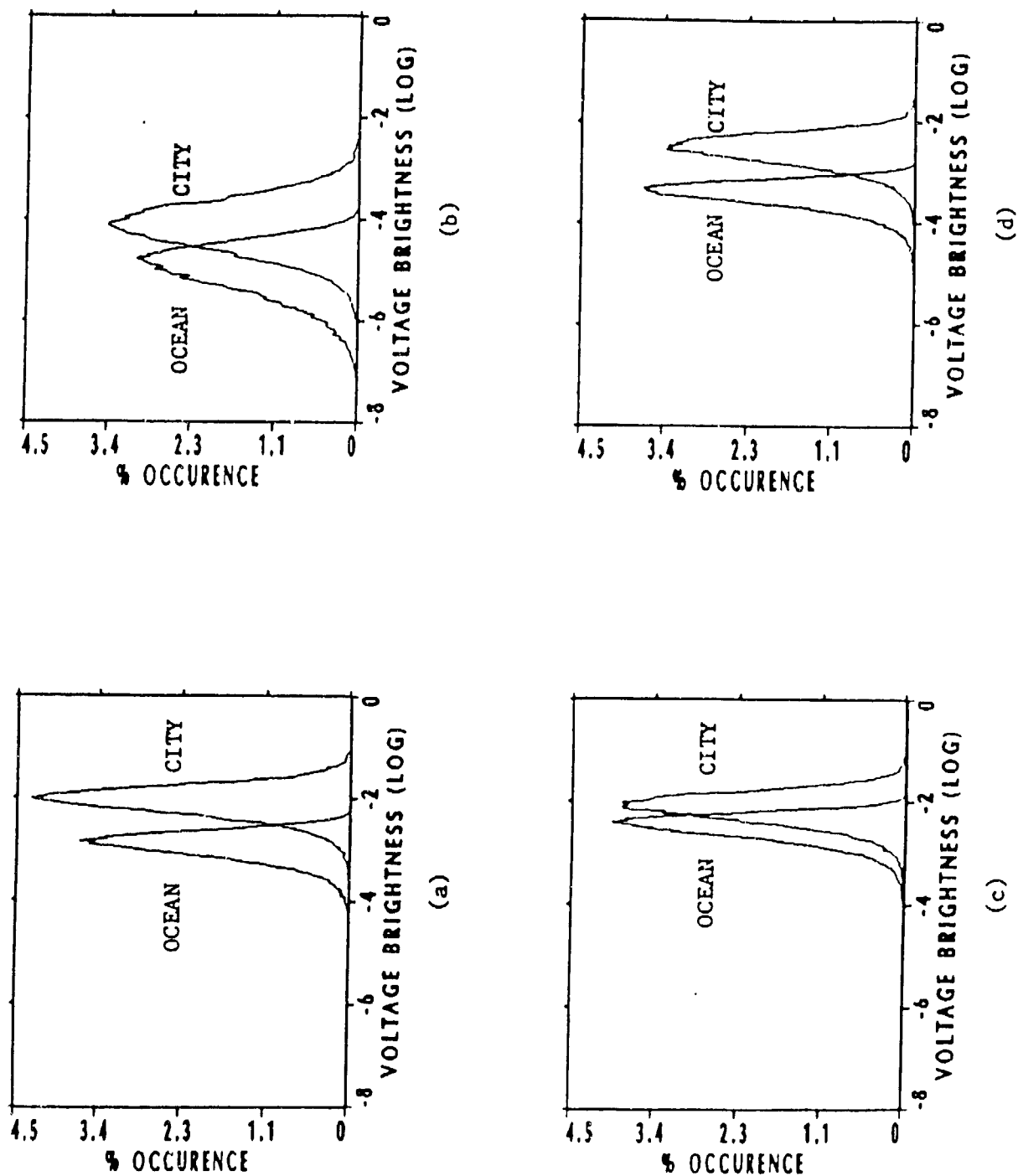


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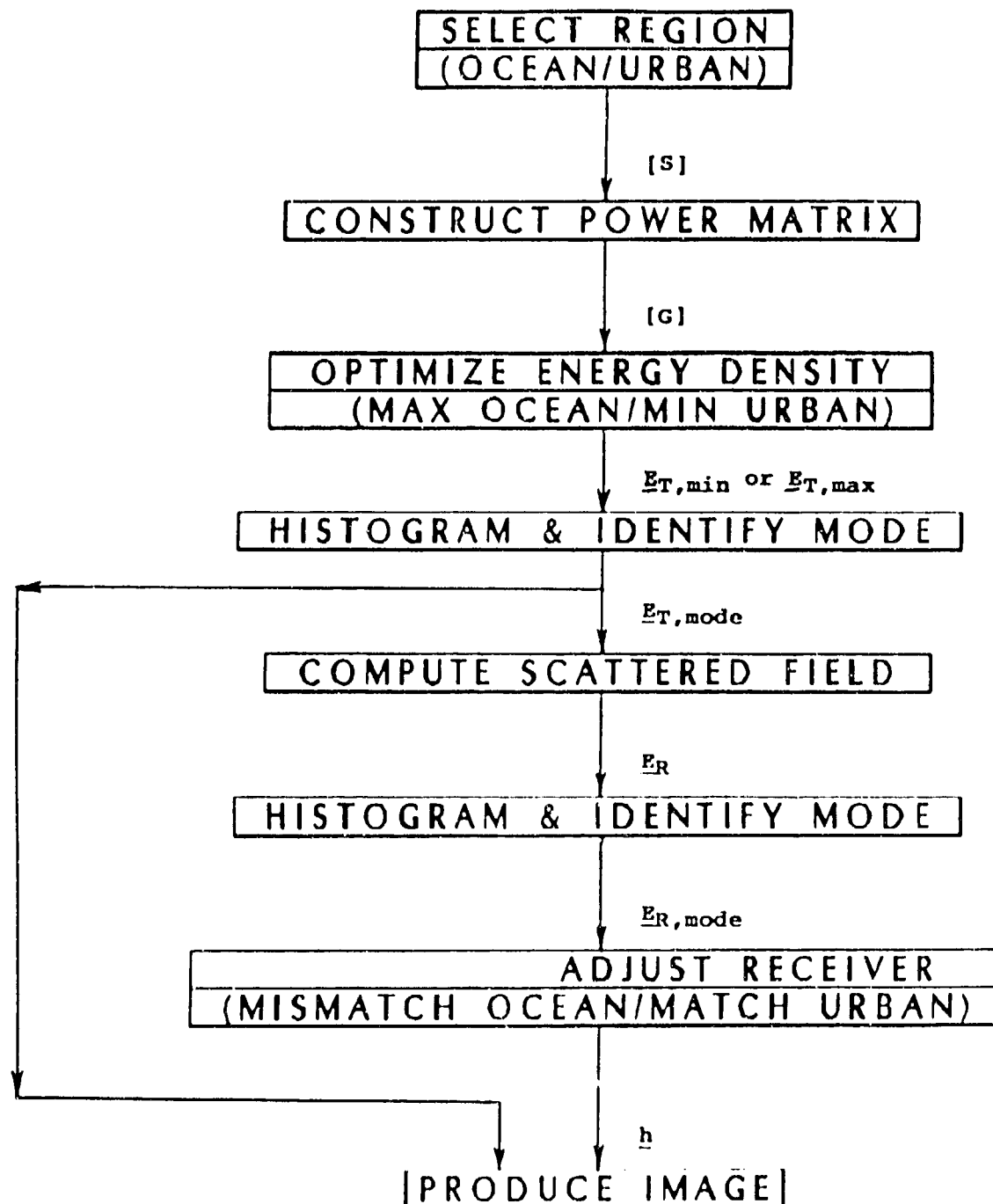


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BACKSCATTER AT X-BAND**

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ABSTRACT

The radar cross section (RCS) scattering matrix data collected by NADC with the APS-116 X-band radar at Molokai, Hawaii are analyzed and interpreted using a simple near-grazing backscatter model. The phase and amplitude behavior of VV, HH, and VH polarized backscattered fields, the null polarizations and the Huynen target parameters near-grazing are examined and the relationship between polarization properties of radar returns and physical parameters including sea state, wind stress is established. A distinctively different behavior between VV and HH backscattering amplitudes are recognized and a possible explanation is given. This study will provide a valuable key as to how the polarimetric backscattered data (both amplitude and phase) can be best processed in the problem of target detection in the sea environments.

1. INTRODUCTION

High-resolution radar backscattering from near-grazing sea surfaces is an important subject matter in target detection in sea clutter environments. Temporal as well as spectral behavior of polarimetric radar backscattering has been studied experimentally and empirical studies on its polarization, radar incidence angle, frequency, and sea-state parameters have been done^{1,2,3}. For instance, it has been long recognized that HH-polarized backscattering from near-grazing sea exhibits spiky returns which sometimes last a few seconds. Extensive experimental studies and data analyses to investigate this peculiar HH-polarized backscattering behavior have been carried out, resulting in a general consensus that white cap formation associated with breaking waves are most likely responsible for this peculiarity of HH-polarized backscatter.

To better understand the relationship between sea-state and radar backscattering, an approach dealing with both amplitude and phase information of VV, HH, and VH polarized backscatter may be necessary. We will refer to this approach as a scat-

tering matrix approach. Since measurements based on the scattering matrix approach provide an additional phase information as well as amplitude, it would, in theory, be possible to completely characterize the nature of a radar target, if it were an ideal discrete stationary object. In this paper, we analyze the amplitude and phase characteristics of VV, HH, and VH polarized backscatter measured by X-band radar.

In the next section, a brief summary on how the data was taken and analyzed is given. In Section 3, the statistical behavior of the amplitude and phase of the sea clutter returns, the co- and cross-polarized null locations⁴, and the Huynen target parameters are presented⁵.

In Section 4, a simple theoretical model explaining the VV and HH backscattering amplitude behavior is given.

2. EXPERIMENTAL DATA ANALYSIS

The scattering matrix data analyzed in this paper are measured for horizontal and vertical polarizations over the sea surface near the grazing angle and at X-band. The data provided are for 32 range bins with the separation of one mile.

The objective of the data analysis has been to generate and display data in a format which assists in identification of radar clutter features and in the development of classification algorithms. For this reason, we have used the raw data to generate and plot the statistical behavior of

- (i) S_{HH} , S_{HV} , S_{VH} , S_{VV} and Span
(S_{pq} 's denote pq polarized elements of scattering matrix),
- (ii) Null polarizations (co-pol and x-pol nulls) on the Poincare sphere. It also includes the analysis of the maximum return (m) in the co-polarized channel, and
- (iii) The Huynen target parameters.

In the analysis, we require $S_{HV} = S_{VH}$ for perform-

ing steps (ii) and (iii). In the given scattering matrix data $S_{HV} \neq S_{VH}$. This is probably because of the lower sampling rate (switching seems to have been much too low) or the different calibration for the H and V polarized signals. In Figs. 1a/b, the S_{HV} and S_{VH} show the same average behavior. Thus, in our analysis, we have considered the value of S_{HV} equal to that of S_{VH} .

The theory used in this analysis is given by many investigators^{5,4,11,12,10}.

3. DISCUSSION OF THE GRAPHS

In the following, the computer plots for the scattering matrix elements, polarization nulls and the Huynen target parameters are examined.

3.1 Amplitude/Phases of the Scattering Matrix Elements

The amplitude and phase behavior of S_{HH} , S_{HV} , S_{VH} and S_{VV} are demonstrated in Figs. 1a/b. It is found that the HH return is greater than the VV return by 10dB. The S_{HH} return is shown to be 25dB. A simple theoretical model explaining the VV and HH return is given in Sect. 4. The cross-polarized returns S_{HV} and S_{VH} are the same. The amplitude of S_{HV} or S_{VH} is 15dB. From the data analysis for a number of bins, it is found that the amplitude of the VV return is comparable to the HV return.

3.2 Relative Co-Polarization Phases

The co-polarization phase difference ($\phi_{HH} - \phi_{VV}$) is shown in Fig. 2. The average co-polarization phase difference for the sea surface is found to be zero. This phase difference, in general, is used in imagery of terrain and vegetation, where the co-polarization phase difference has significant value because of the higher degree of surface roughness (e.g. corn field). In the case of sea surface, it has a rather smooth surface and thus the co-polarization phase difference is very small or zero.

3.3 Null Polarizations

The null polarizations, i.e., two co-pol nulls and two cross-pol nulls are calculated and plotted on the $(\theta - \phi)$ -plane of the Poincaré sphere (see Fig. 3). It is found that co-pol 1 has a wider spread than that of co-pol 2, x-pol 1 and x-pol 2. The average values for co-pol 1, co-pol 2, x-pol 1 and x-pol 2 are found to be $(\theta = 100^\circ, \phi = 180^\circ)$, $(\theta = 90^\circ, \phi = 180^\circ)$, $(\theta = 85^\circ, \phi = 0^\circ)$ and $(\theta = 95^\circ, \phi = 180^\circ)$, respectively. The analysis of the nulls for other bins indicate that the null polarization distribution is changed, however, the average value is the same.

Based on the null polarization theory, the maximum power in the co-polarized channel is calculated and plotted in Fig. 3. The average value of the

maximum return is shown to be 28dB.

3.4 Huynen Target Parameters

The Huynen target parameters $2A_0$, B_0+B , B_0-B , C , F , D , E and G are shown in Fig. 4. The physical interpretation of these parameters in their relationship to the target has been demonstrated by many investigators^{5,13,14}. According to Huynen, A_0 , B_0-B and B_0+B characterize the target's symmetry, non-symmetry and irregularity, respectively. In Fig. 4, A_0 and B_0+B have higher values and B_0-B is zero. Therefore, the sea surface is symmetric and irregular, and the non-symmetry is zero. Irregularity may represent the fluctuating sea-waves of the water surface. The parameter C represents the global shape of the target. For the case of sphere target, $C = 0$, and for line target $C = 2A_0$. From the C-plot, $C = 2A_0$, which represents the flat surface. D is a measure of local shape for convex surfaces. If the local radii of curvature of the specular point on the surface are equal, $D = 0$, otherwise $D \neq 0$. In this analysis, the average value of $D = 0$. The fluctuating parts of the plot represent the irregular curves on the sea surface formed by wind conditions. The parameter E is analogous to parameter D , except that E is most sensitive when the target has circular cross-polarization nulls, whereas D is more sensitive when the target has linear cross-polarization nulls. In Fig. 4, $E = 0$. F represents the target helicity and G represents the coupling parameter of the symmetric and non-symmetric parts of the target. In our case, $F = G = 0$. Since the sea surface contains no non-symmetric property, the coupling between the symmetric and non-symmetric is zero ($G = 0$).

4. SIMPLE BACKSCATTERING MODEL FOR NEAR GRAZING SEA

The polarimetric backscattering from near-grazing sea has been experimentally studied by many investigators, resulting in a consensus that amplitudes of HH-backscatter exhibit a spiky behavior compared to VV-backscatter. These anomalously spiky HH-polarized backscattering amplitudes have been under theoretical study by many investigators^{1,3}, and it is generally agreed that the whitecaps riding on top of breaking sea waves are responsible for the HH-polarization peculiarity. As pointed out in the previous section, the sea backscatter data being analyzed in this study shows that the span (or magnitude) of HH-polarized backscatter turns out to be about 10dB higher than VV-backscatter near-grazing incidence.

In order to explain the higher (or spiky) HH-polarized backscatter behavior, we need to examine the physical geometry of breaking waves which are consequence of nonlinear wave motions. It is known that the wave front of breaking waves tends to steepen until it becomes vertical and furthermore negative⁶. For the purpose of modeling, we assume that the breaking wave is a perfectly con-

ducting wedge such as shown in Fig. 5. Note that diffracted fields from the tip of the wedge can be approximately obtained in high frequency approximation⁷. The ratio between HH and VV polarized backscattering coefficient is given as

$$\frac{\sigma_{HH}}{\sigma_{VV}} = \left(\frac{u_1 - u_2}{u_1 + u_2} \right)^2$$

where

$$u_1 = \frac{\frac{\pi}{Y} \sin\left(\frac{\pi^2}{Y}\right)}{\cos\left(\frac{\pi^2}{Y}\right) - 1}$$

$$u_2 = \frac{\frac{\pi}{Y} \sin\left(\frac{\pi^2}{Y}\right)}{\cos\left(\frac{\pi^2}{Y}\right) - \cos\left(\frac{\pi}{Y} 2\phi\right)}$$

Refer to Fig. 5 for angles ϕ and γ .

Fig. 6 shows the ratio between HH and VV polarized backscatter versus incidence angle for two different wedge angles. The result depicted in Fig. 6 implies that the diffraction phenomena resulting from wedge-like sea waves are responsible for higher HH-backscatter. It is worthy of note that HH backscatter from water spray or droplets existing over sea wave cannot be expected to be higher than VV backscatter. This speculation is based on the theoretical study which shows that VV and HH backscatter from isotropic Rayleigh and Mie spheres (ensemble of volumetric spheres) turn out to be the same^{8,9}.

5. CONCLUSIONS

The behavior of null-polarization characteristics and Huynen target parameters was investigated using the near-grazing sea backscattering data at X-band. It was found that the average values of HH, HV, VV returns and null-polarization locations are unchanged for different range bins. The Huynen target parameters were shown to be useful for characterizing the geometric features of sea surfaces. A simple wedge scattering model was used to explain the higher HH-backscattering level over VV-backscattering. Diffraction phenomena from the tips of breaking sea waves was suggested to be a responsible scattering mechanism for often-observed spiky HH-polarized sea radar backscattering near grazing angle.

6. ACKNOWLEDGEMENTS

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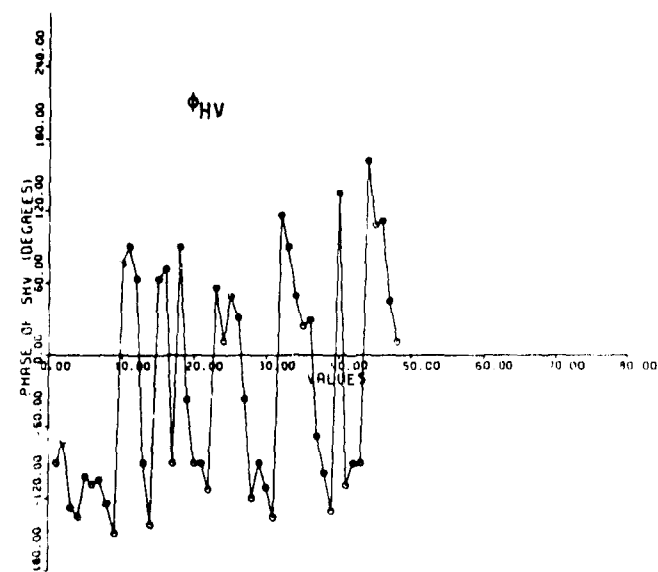
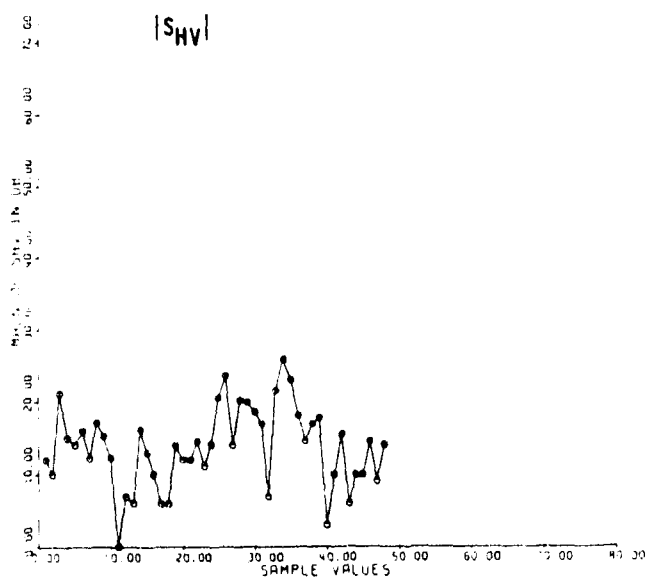
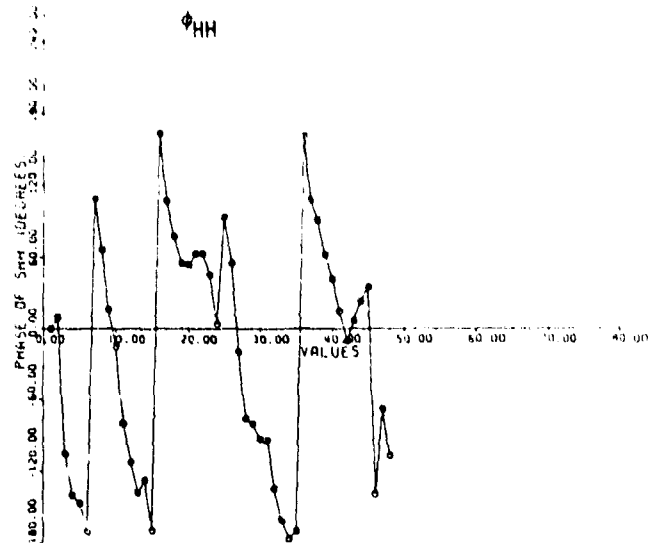
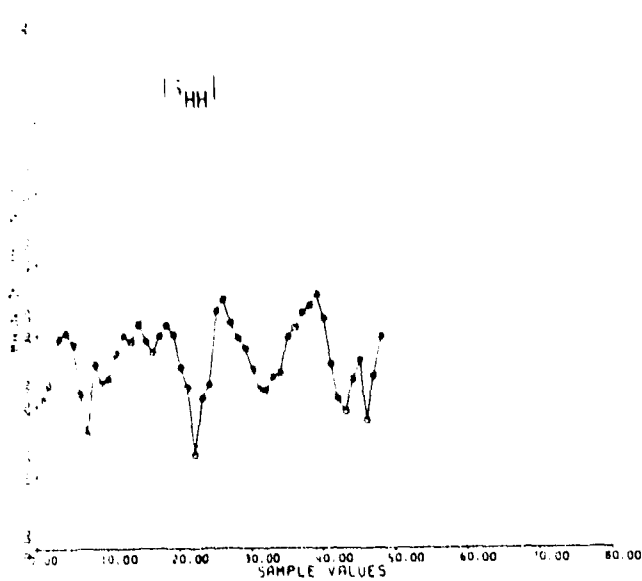


FIGURE 1A: AMPLITUDE AND PHASES OF THE SCATTERING MATRIX ELEMENTS FOR HH AND HV

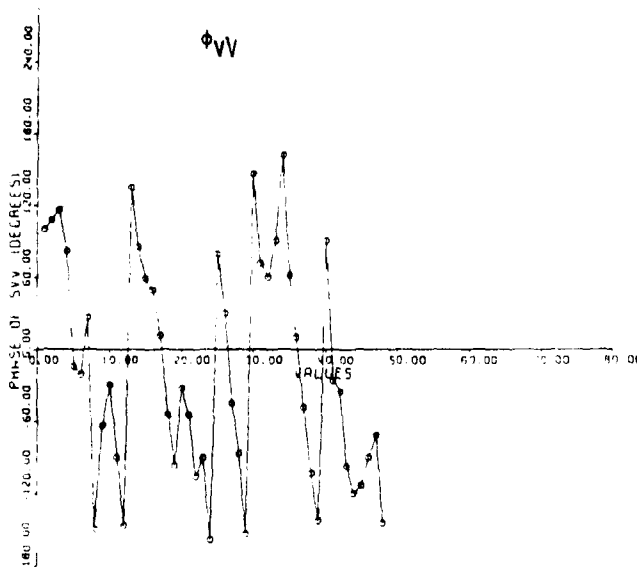
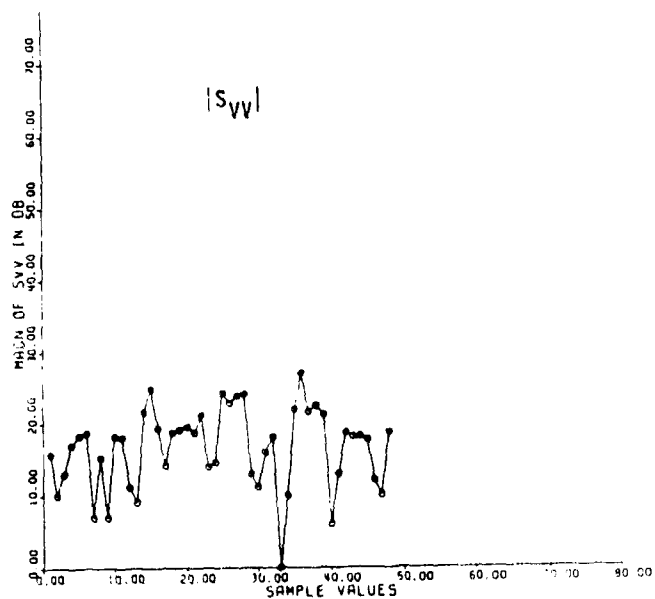
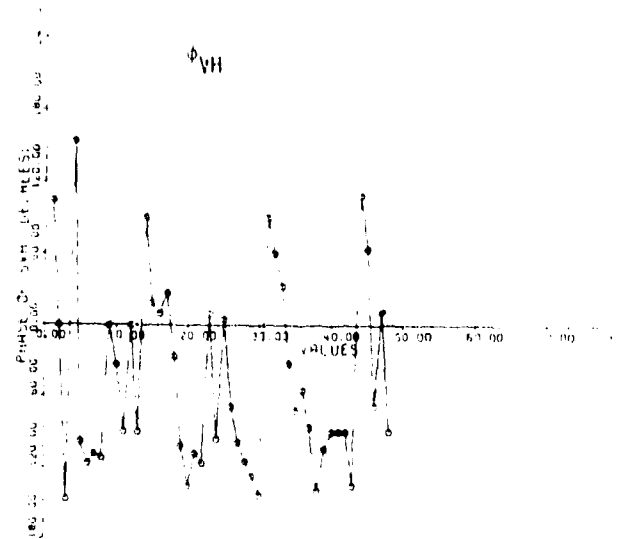
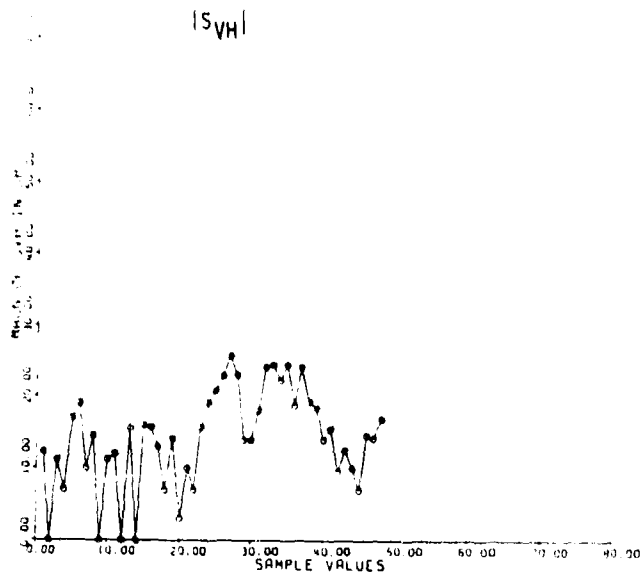


FIGURE 18: AMPLITUDE AND PHASES OF THE SCATTERING MATRIX ELEMENTS FOR VH AND VV

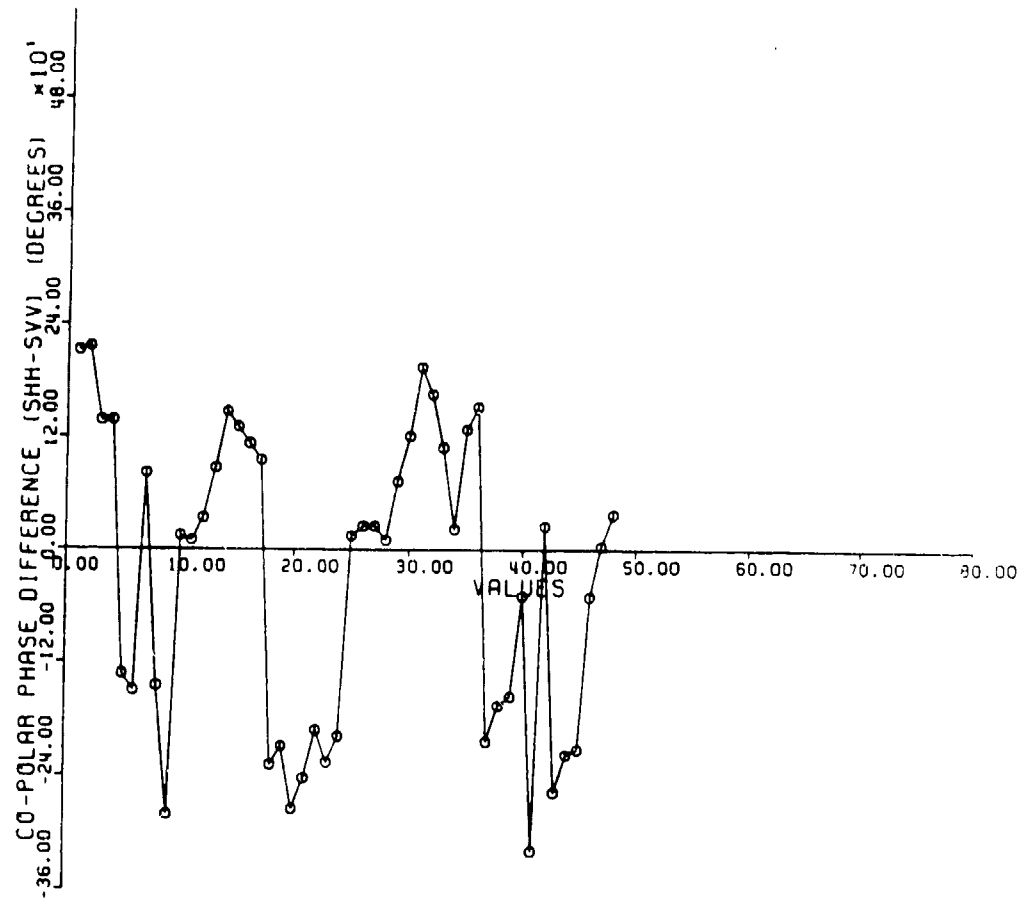


FIGURE 2: RELATIVE CO-POLARIZATION PHASES

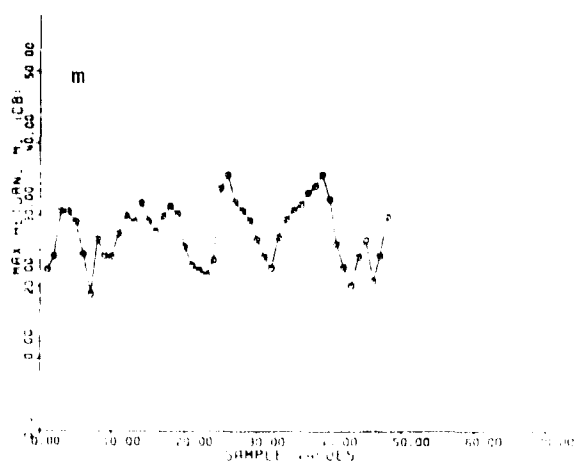
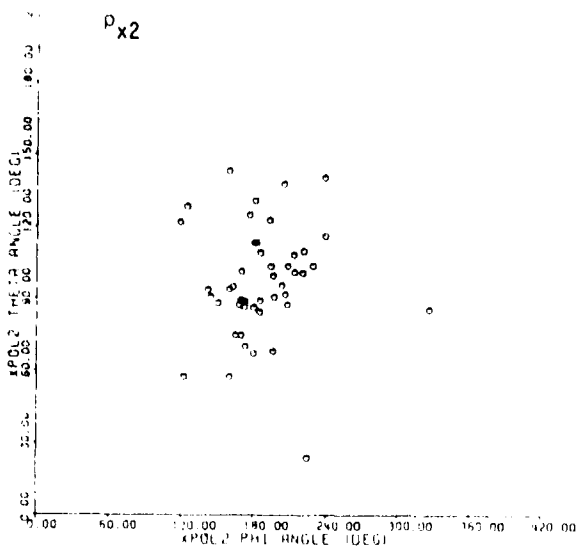
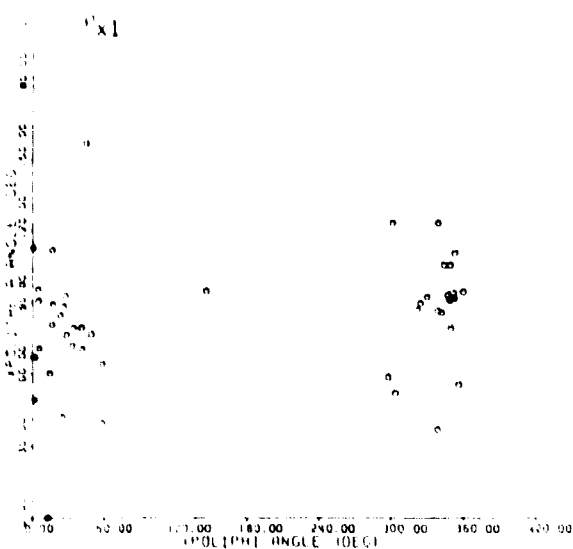
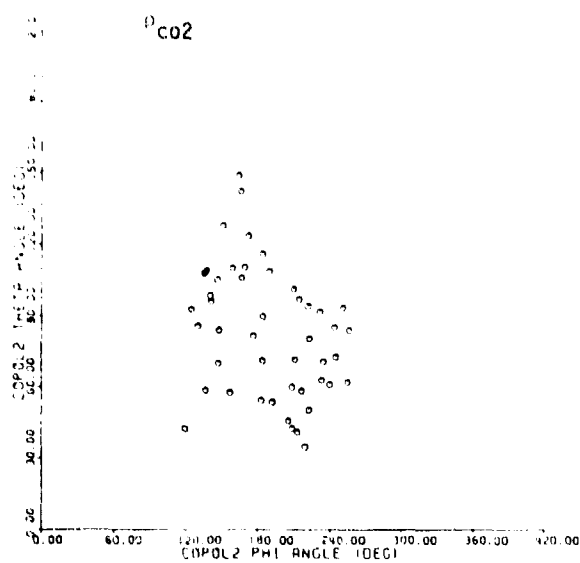
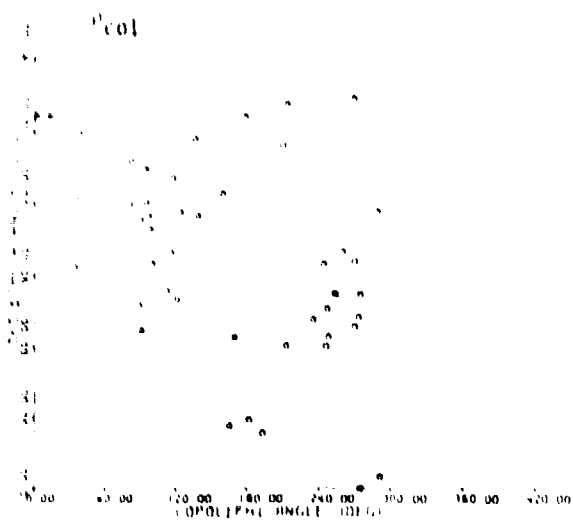


FIGURE 3: NULL-POLARIZATIONS AND THE MAXIMUM RETURN

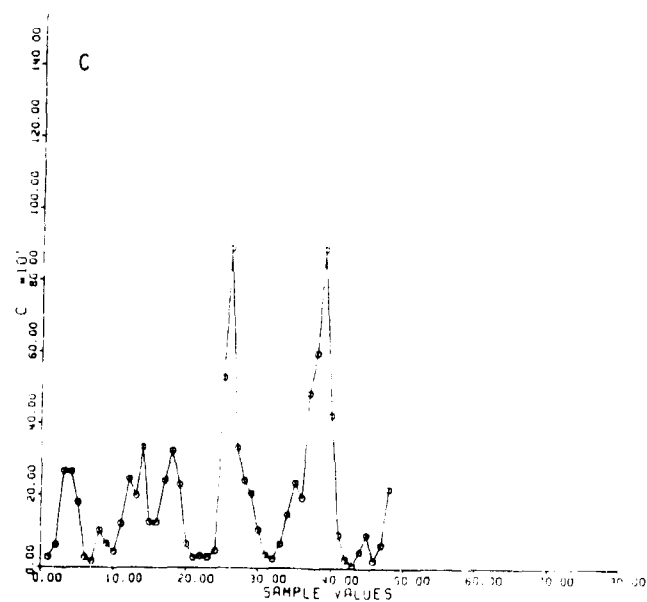
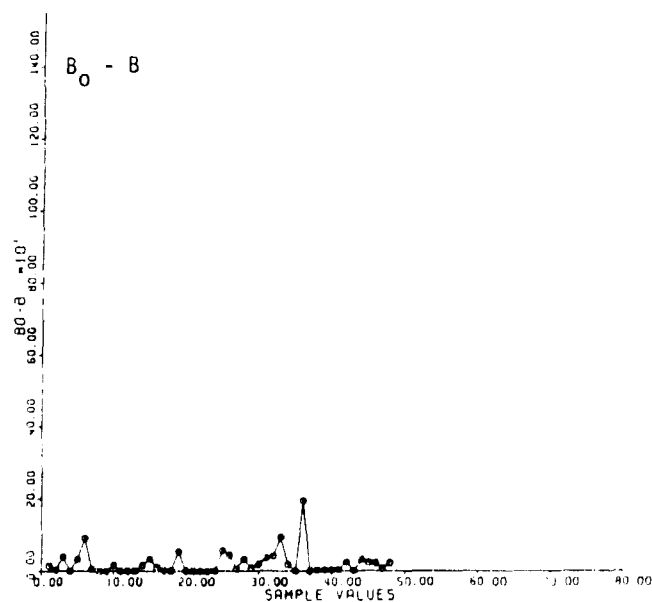
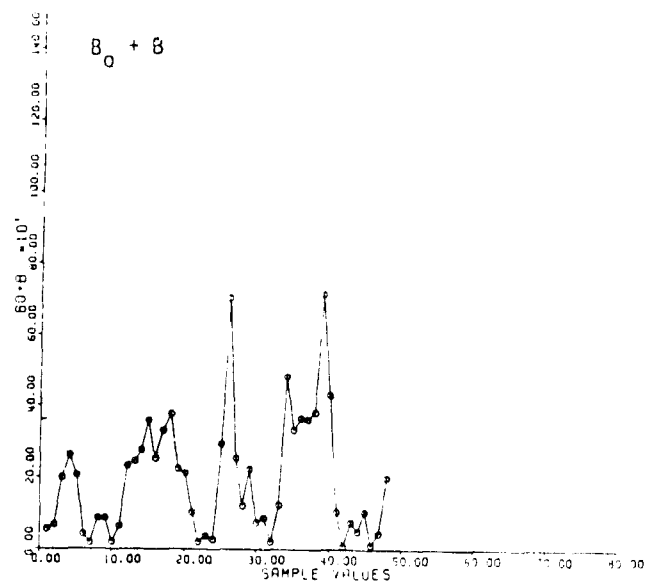
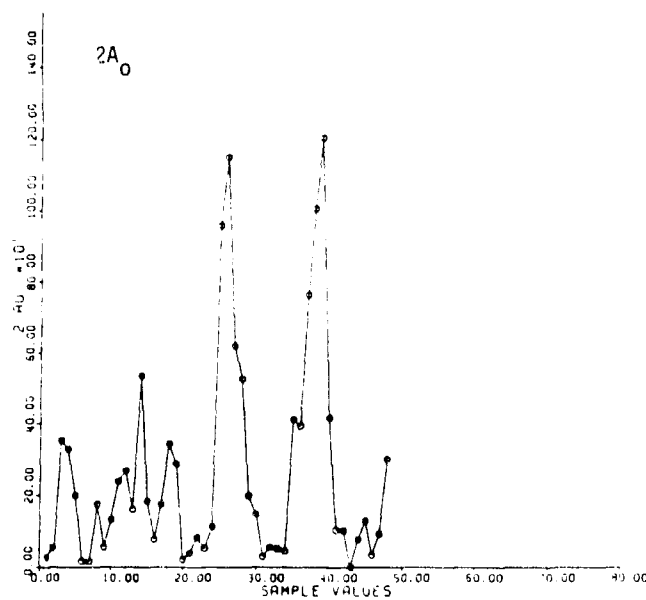


FIGURE 4A: HUYNEN TARGET PARAMETERS, $2A_0$, $B_0 + B$, $B_0 - B$, and C

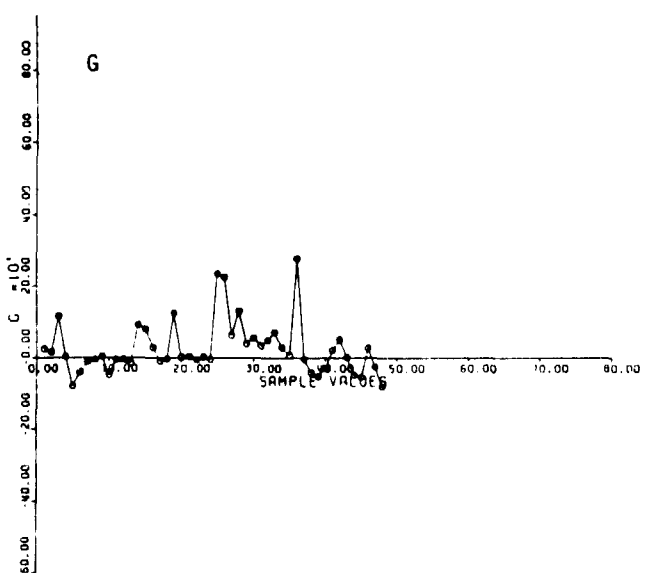
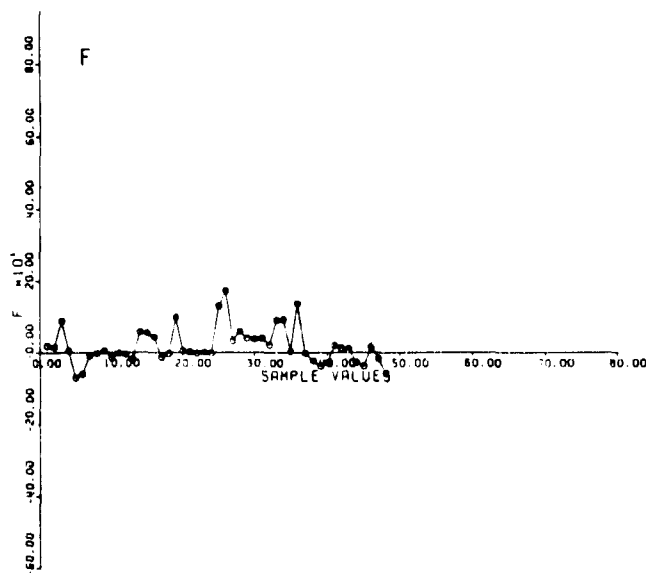
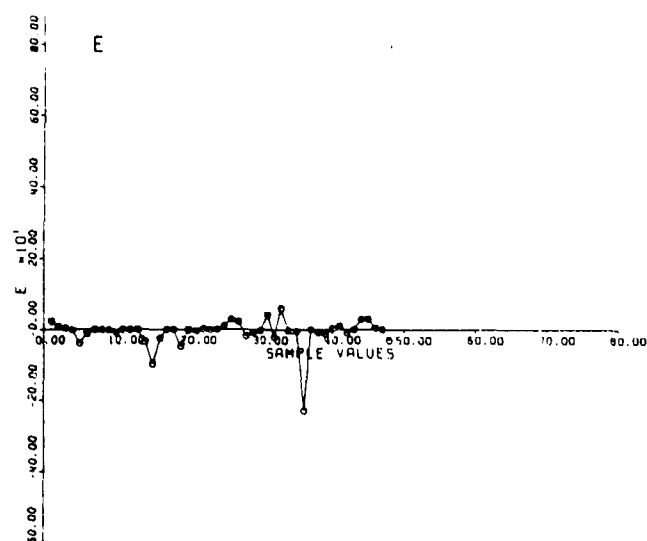
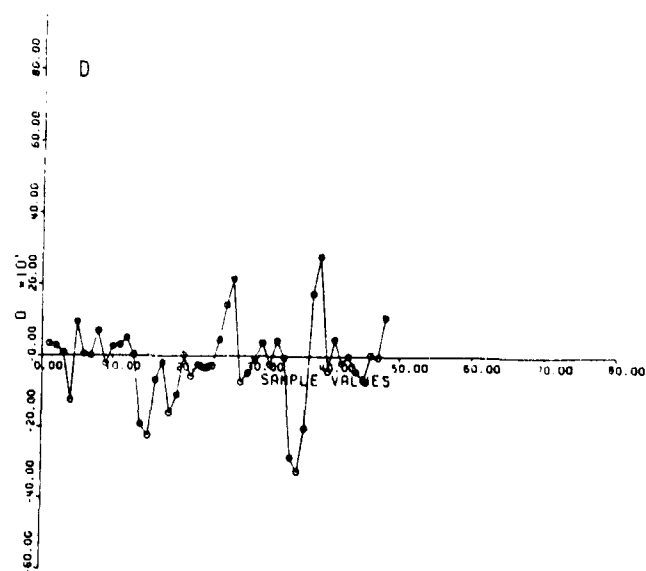


FIGURE 4B: HUYNEN TARGET PARAMETERS, D, E, F, AND G

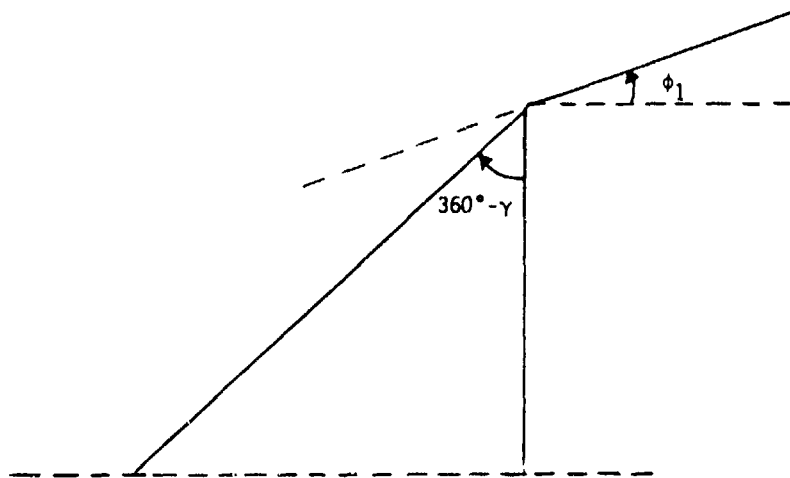


FIGURE 5: BREAKING SEA WAVE MODELED AS A PERFECTLY CONDUCTING WEDGE (WEDGE ANGLE = $360^\circ - \gamma$, GRAZING ANGLE ϕ_1 , $\phi = \phi_1 + 90^\circ$)

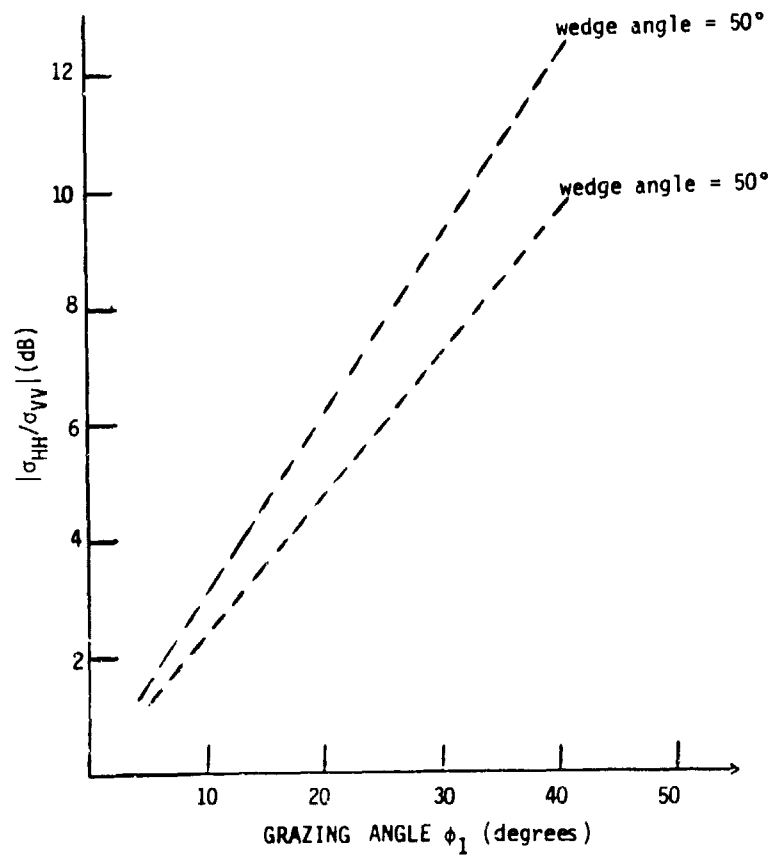


FIGURE 6: RATIO BETWEEN $|\sigma_{HH}|$ and $|\sigma_{VV}|$ OF WEDGE BACK-SCATTERING VERSUS GRAZING ANGLES

THE ELECTROMAGNETIC INVERSE SCATTERING PROBLEM - CURRENT STATE-OF-THE-ART

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ABSTRACT

This introductory overview provides a succinct summary of various monographs on electromagnetic inverse problems including a concise definition and description of the problem and an extensive list of pertinent references. Specific results are not summarized here but will be presented during various other lectures on selected electromagnetic vector inverse methods useful in high resolution radar-target/clutter-imaging which are being outlined in this paper.

INTRODUCTION: FORMULATION OF THE GENERAL INVERSE PROBLEMS

Inverse methods or inverse modeling engulf an enormous range of problems in many spectral regions of EM wave interrogation in which remote sensing/probing observations provide measurement data about components of the scattered EM fields (frequency, amplitude, polarization, phase, doppler) from which information about the geometrical and physical properties of the object (size, shape, material decomposition, motion, etc.), which cause the scattering, is sought. Most often the observed data are incomplete in various ways so that the inverse problem becomes ill-posed, i.e., does not possess convergent solutions. Indeed, some of the most encouraging advancements made in recent years have been on the development of mathematical methods for inverse modeling which have lead to the formation of the new applied mathematical, engineering sciences discipline of "General Profile Inversion" or simply "Inverse Methods". As relates to electromagnetic remote sensing, it seems that mathematical aspects at the present time are ahead of the technology in the sense that we have not yet realized optimal equipment and parameter design for illuminating inaccessible (remote) objects whose detailed structure we wish to detect/discriminate against background clutter, leading to imaging, identification and/or ultimately classification. Thus it is central to the development of inversion techniques for remote sensing, geo-electromagnetic sounding, or electromagnetic/nuclear magnetic resonance probing of various types of surfaces with voluminous over/under-burden, at rest or in motion, that transmitting and receiving devices, together with analog/digital signal/image data processing techniques be optimized in coordination with the associated "ground-truth metrology" in order to take full advantage of the advances accomplished in mathematical analysis, modeling, simulation and understanding provided by "Inverse Methods".

GENERAL OVERVIEW

A first extensive survey covering many fields in which inverse methods may be applied is compiled in a NASA memorandum by Colin [1] which has proven to be a major source for many more studies; more succinct introductions to inverse problems have been given in Sabatier [2], Newton [3], Keller [4], and Parker [5]. A thorough literature review of many aspects of inverse methods in electromagnetics has been presented by Boerner [6,7] and more recently the inverse sources, scattering and imaging problems were treated in Baltes [8,9] and Devaney [10], respectively. Especially, the Special Issue on "Inverse Methods in Electromagnetics" of the IEEE Transactions on Antennas & Propagation, AP-29(2), March 1981 (eds: W-M. Boerner, A.K. Jordan, I.W. Kay) [11] and the Proceedings of a recent NATO-

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University of York, UK
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Advanced Research Workshop on "Inverse Methods in Electromagnetic Imaging", organized, executed and edited by W-M. Boerner [12] cover such topics as fundamental inversion theories [12:I], numerical instabilities [12:II], utilization of polarization information [12:III], effects of environmental noise and clutter [12:IV], and holographic and tomographic imaging and their associated phase retrieval problems [12:V]. In addition, the working discussion group reports [12:VI] provide an excellent assessment of the current state-of-the-art with identification of the still unresolved questions. We refer to the NATO-ARW IMEI [12] because the seventy-five review papers contain an almost complete list of references including those of other related NATO-ARW/ASI proceedings on the subject matter [12:0.2].

MATHEMATICAL TREATMENTS

An illuminating exposition on mathematical and theoretical aspects of the inverse scattering problem was recently given by Sabatier [13], who is also the organizer of the annual "Recontre Problems Inverses (RCP-264)" at the Universite des Sciences et Techniques de Languedoc, Montpellier, France, of which the annually issued proceedings provide a very good account of the continual current progress made on the mathematics of profile inversion and its engineering sciences applications [14].

Special emphasis is to be given to the mathematics of generalized inverses [15] and the generalization of the Moore-Penrose Inverse [16]. Of basic importance to the electromagnetic inverse problems for shape-reconstruction is the Minkowski-Hurwitz-Hilbert problem of inverse differential geometry [17] in which a transform procedure is introduced to map the topological image of a closed convex surface onto the unit sphere of directions [18] in terms of principal curvatures. In many two- and/or three-dimensional wave transmission and reflection density profile as well as shape reconstruction methods, the theory of reconstruction from projections becomes of fundamental importance, which was introduced by Lorentz [19] and formulated by Radon [20], who established all the basic relationships existing between the transforms image, projection and Fourier spaces. Whereas, the theory is well treated in John [21], the rapidly increasing number of applications to projection tomography in medicine [22] and its extension to diffractive tomography [23] in ultrasonic and microwave imaging [24], geophysical wave migration [25] and radar target imaging [26] including Synthetic Aperture Radar [27] and Inverse Synthetic Aperture Radar [28] must be emphasized.

In one way or another most inverse problems used in remote sensing and electromagnetic imaging deal with the inversion of the wave equation [1,29] which, for the case of radio waves was discussed in detail, for example, in Budden [30], Clemov [31], and most recently in Ishimaru [32] and Devaney [10], where in many solutions use is made of the Abel inverse transform [33] of the classical Wentzel-Kramers-Brillouin (WKB) approximation [29] in problems of a slowly varying one-dimensional profile. Considerable extensions of these inversion methods were obtained for the inhomogeneous wave equation in quantum mechanics known as the Gel'fand-Levitan-Marchenko [34,1] procedure which has been the topic of considerable interest since

closed-form expressions for the scattering potential can be found [40-42]. It should be noted that extensions of the Gel'fand-Levitan-Marchenko procedure have become of considerable interest in the solution of non-linear problems [43], particularly solitary wave mechanics [44] and at phase transitions and instabilities [45].

GEOPHYSICAL INVERSE PROBLEM

Another startling extension of the regularization method may be seen in the optimum strategy (maximum entropy) method applicable to the inversion of limited data sets which was introduced by Backus and Gilbert [47,48] and since has found many applications also in other disciplines [50], and it was also found well suited to treat a class of nonlinear inverse problems of the solitary wave type [43]. Today, geophysical inverse methods are widely used in exploration seismology [51-56], where in essence the time of arrival of seismic pulses at various locations, generated by sources at different locations, i.e., the "wave migration" [53] method, is used to formulate the problem in terms of nonlinear functionals. Considerable advances have been made in spectral estimation [57], seismic signal processing [58], and especially in geotomography [59]. We refer to the recent Special Issue on Geotomography, edited by the late R. Jeffrey Lytle [59], whose extensive contributions to electromagnetic imaging are here acknowledged with praise and admiration (see also IEEE APS Newsletter, Feb. 1986, vol. 28(1), p. 26), where various extensions of transmission projection tomography are discussed. Of great future importance is the rapid advancement of vertical seismic profiling [60] which represents an extension of scalar inverse methods and permits inverse solutions for reflection and refraction seismology in elastic media where, in addition to the longitudinal compressional wave P, the S-wave components are taken into account resulting in a truly tensorial inverse problem [61].

MEDICAL INVERSE PROBLEM

Inverse methods have always played, and more explicitly are playing an increasing role in medical imaging [62,65], where conventional X-ray radiography has almost become obsolete and is being replaced by X-ray computer-assisted tomography (CAT SCAN [66,22]) and more recently by electromagnetic/nuclear magnetic spin resonance imaging [67-69], also known as Zeugmatography, which is well reviewed by Schwierz [70]. In addition, we need to refer to recent advances made in ultrasonic [71,23,24] as well as microwave [23,61] medical imaging, and it is here safe to say [72,73] that medical diagnosis of biological systems by non-ionizing acoustic as well as electromagnetic waves is on a steady increase [71,72,74], and applicable imaging procedures in particular require solutions to the inverse problems of wave propagation in strongly inhomogeneous media [75,61].

AERONOMIC REMOTE SENSING

Electromagnetic and acoustic inverse methods have long been an integral part of aeronomic remote sensing [1,11,12,32,76-84] using both passive and active wave sounding, where usually the Born and Rytov approximations [10,12] for slowly varying index profiles are relevant. Whereas in the microwave region coherent methods developed in radar are more likely to be used [12,78,80,84,85], in the infrared and optical regions incoherent properties need to be taken into account as well [1,6-12,31,32,76-89]. Specifically, we refer to Baltes [8,9], Towney [87], Depak [76], Zuev [8], Zuev and Hinkley [83], Jeske [84], and a recent NATO-ASI on the subject matter of optical metrology [89], in which most recent treatments on inverse methods in laser remote sensing are presented. Image formation from coherence functions is also a basic inverse problem in astronomy [90] and we refer especially to Lillesand [91], Bernstein [88], Wilde and Barrett

[92], Egan [93], Gehrels [94], and Bohren and Huffman [95]. We also should mention here that Radon's projection transform theory [20-22] has also become a very useful tool in radio astronomy [90] as was first shown by Bracewell [96]. Similarly various interferometric and holographic image reconstruction methods [10-12] are relevant, for example, the X-ray astronomical imaging techniques developed by Oda [97]. Another wide field of applications of electromagnetic inverse methods includes ionospheric/magneto-spheric probing [98-100] as well as probing of the Earth's crust and mantle [101], which also deserves a separate treatment.

THE ELECTROMAGNETIC INVERSE PROBLEM

After having provided an overview of inverse problem in related areas, we shall now scrutinize those methods and techniques which look promising to be applied generalized to the three-dimensional electromagnetic vector case, i.e., the case in which polarization effects must be considered and which may be defined as follows:

Whereas, on the one hand, in the direct problem of electromagnetic diffraction and scattering total a priori information on the size, shape, and material constituents of scatterer, the incident field vector and its orientation with respect to the fixed scatterer coordinate system is given, and the scattered field is to be calculated everywhere over the total frequency domain and for all aspects. On the other hand, in the inverse problem we need to recover the size, shape and constitutive characteristics of an a priori unknown scattering target with the knowledge of the incident and the resulting scattered field data [6,7,11], usually provided over limited domains of aspect angle, frequency and polarization.

Exact solutions of the direct problem of EM scattering satisfying Maxwell's equations are possible only for a limited number of canonical, perfectly conducting shapes [102]; and for more complex conducting and/or nonconducting shapes approximate methods need to be used [103] which are based on approximate boundary conditions, e.g. the Kirchhoff high frequency or the Leontovich scalar impedance approximations [104]. The exact solution to the electromagnetic inverse problem would require the inversion of Maxwell's equations or of the vector diffraction integral [105], which do not exist and other methods must be sought. Several limited attempts at deriving exact electromagnetic inverse scattering theories have been made and we refer here to an approach of generalizing the Gel'fand-Levitan method of quantum mechanics [34-42] to the electromagnetic case [40-42], or the introduction of electromagnetic inverse boundary conditions [104] which depend neither on the a priori knowledge of the shape or the material constituents of the scattering body, but allow to specify those characteristic parameters uniquely from the near field data which need to be recovered from far-field measurements. However, either method requires highly precise and complete sets of measurement data in frequency (broadband), amplitude, phase and polarization.

APPLICATION OF ELECTROMAGNETIC INVERSE METHODS TO HIGH RESOLUTION RADAR IMAGING

It has especially been the rapid advancement of electromagnetic m-to-sub-micron wavelength remote sensing, probing, sensing and imaging demands which has forced the rapid growth of electromagnetic inverse scattering, diffraction and of new analyses of the radar cross section [102,103], and especially of the polarimetric (RCS) scattering matrix [106-108]; and we refer here especially to several monographs and books dealing with sonar, radar and lidar [79,80,84,109-111]. Specifically, we need to stress the importance of the complete utilization of polarization

information [112,113] in synthetic aperture radar imaging which will be the subject of another succinct state-of-the-art summary on "Fundamentals of Radar Polarimetry" [112]. Namely, it is very important to understand that both vector inverse scattering theories as well as polarimetric (scattering matrix) radar theory, metrology and the related high precision ground-truth metrology must be developed simultaneously and this has been the past, current, and is the future main research objective of the author.

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RECENT ADVANCES IN RADAR POLARIMETRY - ASSESSMENT OF THE HISTORICAL DEVELOPMENT

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ABSTRACT

This introductory paper provides a succinct overview of the historical developments in radar polarimetry highlighting important contributions and including concise definitions and descriptions of the scattering matrix operations, and the polarimetric target (desired signal/image) versus clutter (undesired signal/image) optimization problems. A historical events table together with a list of pertinent references is provided together with a critical review on the validity of various polarization dependent approaches to radar target phenomenology. Specific results are not reported here, but will be the subject of other lectures on selected topics on fundamentals of radar polarimetry and its applications to high resolution polarimetric radar imaging.

INTRODUCTION

Radar polarimetry has become an indispensable tool in modern electromagnetic sensor technology both in the civil and the military sectors and also in remote sensing and radar meteorology. From the outset, we wish to emphasize that by incorporating coherent polarimetric phase information into radar signal and image processing one can anticipate a breakthrough which is at least comparable to that brought about by the advent of holography and computer assisted tomography and its applications to Synthetic Aperture Radar (SAR) and Inverse Synthetic Aperture Radar (ISAR). Although considerable R&D efforts have already been expended during the past three decades, there still exist many "grey areas" in both theory and techniques of radar polarimetry which is best illustrated by the following recent true event:

"... Circularly polarized waves have either a right-handed polarization or a left-handed polarization, which is defined by convention. The TELSTAR satellite sent out circularly polarized microwaves. When it first passed over the Atlantic, the British station at Goonhilly and the French station at Pleumeur Bodou both tried to receive its signals. The French succeeded, because their definition of sense of polarization agreed with the American definition. The British station was set up to receive the wrong polarization because their definition of sense of polarization was contrary to our definition..."

from J.R. Pierce, "Almost Everything About Waves", MIT Press, Cambridge, MA, pp. 130-131, 1974.

In an effort to clear up some of these still remaining misconceptions, it is useful to first present a historical development of the theory of polarization, the fundamentals of radar polarimetry, and then of the intrinsic facility of polarization visualization by insects, fish and mammals. Based on such a critical historical assessment, the appropriate formalism for handling basic polarimetric radar concepts may then be introduced providing clarifications and justifications.

HISTORICAL DEVELOPMENT

The history of polarimetric radar can be traced from the first recorded analytical descriptions of polar-

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ized light. In the following, we shall first discuss the discovery of the properties of polarized light in nature Können [1], of insects, fish and man's facility to observe polarization, and then of the discovery of the phenomenon of polar electromagnetic energy spanning the entire electromagnetic spectrum and in particular the m-to-sub-mm-wavelength regions.

Historical Discovery of Polarization

The discovery of the phenomenon of polar electromagnetic energy dates back to at least 1669, when the first known work on the subject was published by Erasmus Bartolinus. It contained his observations that objects viewed through a crystal doubled and that an incident light ray split into ordinary and extraordinary rays Können [1].

Bartolinus was followed by Christian Huygens, who contributed most significantly to the field of optics by proposing the wave nature of light and by his discovery of polarized light (1677). E. Louis Malus proved Newton's suggestions that polarization is an intrinsic property of light and not something added by a crystal (1808). The next significant contribution to this field was added by Augustin Fresnel (1788-1827), who proposed that light could be considered as a transverse wave. His reflection formulas deduced from experimentation are still in use today and have been rederived using rigorous electromagnetic theory by Paul Drude in the late nineteenth century (1889). The last of the early pioneers was Sir David Brewster, who by extending the work of Mallus, discovered the relationship between the polarizing angle and the relative refractive power of dielectric materials (1816). The transition to the formulation of a rigorous electromagnetic theory was paved by Michael Faraday with his postulations of the physical laws of electromagnetism in 1832 which was soon followed by his discovery in 1845 of the rotation of the polarization plane in magnetic fields. In 1852 George Gabriel Stokes laid the foundations of mathematical theories to describe polarized, unpolarized and partially polarized streams of light by introducing his four parameters now known as Stokes parameters.

In 1873 James Clerk Maxwell succeeded in providing a rigorous formulation of Faraday's postulates which led to the formulations of the diffraction theories by Helmholtz (1881) and Kirchhoff (1883) and a strict mathematical treatment was then provided by Arnold Sommerfeld (1896) and earlier by William O. Strutt (Lord Rayleigh) (1881). A significant contribution to the understanding of polarized light was made in 1892 by Henri Poincare, who showed that all possible states of polarization could be represented by points on the Riemann (1872) sphere, the latitude and longitude of each point defining the eccentricity and inclination of the polarization orientation angle of the polarization ellipse. Based on these discoveries, soon to follow, in 1886, was Heinrich Hertz's demonstration of the application of the electromagnetic theory as it applies to lower frequencies such as radio waves which marks the advent of modern applications of electromagnetic waves leading to radio wave communication, object detection and ranging. A good paper was first written by Marconi (1922). The work of most of these scientists is available in a

translated form in the literature collected by William Swindell [2] and also portrayed in Born and Wolf [3], Skolnik [4] and Boerner [5].

Historical Development of Radar Polarimetry

The use of radio-to-microwaves frequencies for aircraft detection and the design of the first radars was accomplished concurrently in Europe and America by the 1930's and further advanced during World War II (1939-1941) [5].

Very important early basics on the properties of partially polarized waves were discovered by Norbert Wiener (1927-1929) on harmonic analysis in quantum mechanics showing that the coherency matrix is a linear combination of the Pauli spin matrices with the Stokes parameters which had direct influence on the later work of R. Clark Jones (1941-1944) under the guidance of Professor Hans Mueller at MIT. Earlier on in 1926-29 Wolfgang Pauli introduced the concept of the spinor in quantum mechanics which has proven to also become an ideally successful tool in the proper description of polarimetric problems. Then extensive polarimetric wave propagation analyses were carried out at MIT leading to the so-called Jones calculus (Azzam and Bashara, 1977) [6], which now has also become of great value to forward scattering radar analyses, for example, in polarimetric radar meteorology.

The first extensive study on radar polarization was initiated by George Sinclair in 1946 at the Ohio State University, Antenna (later called Electro-Science) Laboratory. He showed that a radar target could act as a polarization transformer and he expressed the properties of a coherent radar target by the 2×2 coherent scattering matrix [S]. These studies were further pursued by Victor Rumsey (1949-1951) and particularly by Edward Morton Kennaugh (1948-1954, 1952). Other basic studies were conducted by Booker (1950), Deschamps (1951), Kales (1951), Bohmert (1951) and Gent (1954) and here we refer particularly to the series of papers in Proc. IRE, May 1951, in which the paper by Deschamps (1951) is still of particular use today. Based on these studies, Kennaugh (1952) introduced a new approach to radar theory and developed the "Optimal Target Polarization Concept" for the monostatic relative phase case which already became of particular interest in meteorological radar studies (circular polarization rain clutter rejection or cancellation). There were a number of other isolated studies initiated, for example, the GIT-Project A235 (July 1955) for the purpose of using polarization to distinguish between targets and clutter, which was well reviewed and summarized by Root [7]. The decade of the fifties closed without any real recognition for the need of decoy discrimination, and theory and techniques of polarimetric radar still remained highly underdeveloped. However, an extensive amount of measurements on the relative phase scattering matrix were made in the late fifties by J. Richard Huynen (May 1960) at the Lockheed Aircraft Corporation who exploited Kennaugh's optimal target polarization concept and developed during the sixties his approach to radar target phenomenology which is reported in his dissertation (1970). Except for the pioneering polarimetric radar developments by Andre J. Poelman, no other relevant studies on radar polarimetry were carried out in the West, whereas we note that in the Russian literature (Kanaevykin et al, 1965, 1968; Varshanchuk and Kobak, 1971; Zhivotovski, 1973, 1978; Bogorodsky et al, 1980) the potential applicability of radar polarimetry to target/clutter analysis was recognized long ago. We also note here that Copeland (1960), under the guidance of Kennaugh, developed a first practical scheme for classification and possible identification of radar targets which also was later-on utilized by Huynen (1960-1970), based purely on radar polarimetric concepts for symmetrical, reciprocal targets [8].

No real progress was made in advancing the fundamentals of radar polarimetry until the early eighties when a renewed effort was made at UIC-EECS/CL in Chicago, IL to assess, most critically, the previous works of Kennaugh and Huynen and to generalize the target characteristic operator concept to the general bistatic case giving special consideration to polarization scattering matrix measurements in any orthogonal elliptic basis [9 to 17].

Visual Observations of Polarized Light by Insects, Fish and Mammals

Insects (bees, ants, hornets, wasps, water fleas, fruit flies), cray fish, eels, some fish and also some mammals are able to distinguish between polarized light and unpolarized light as easily as we can distinguish colors Können [1]. When making use of this ability to orientate themselves using polarimetric parameter manipulations, these animals sometimes perceive the orientation and ellipticity of light at very low (10%) degrees of polarization, and use these inputs for controlling dynamic flight motion even under the severest storm conditions. Man on the other hand, is almost "polarization-blind" and, generally, has to use a polarizing filter to determine the polarization of light. Nonetheless, when light has an extremely high degree of polarization (e.g. >60%), most humans can still perceive polarization with the naked eye when properly trained to observe the so-called Haidinger's brush which was discovered by Haidinger as early as 1844. It turns out that in a plane emitting polarized light, we may see a tiny yellowish figure appear, which we do not perceive in unpolarized light. The orientation of this so-called Haidinger brush depends on the direction of vibration of light and co-rotates if this plane is rotating. If one wishes to visualize the outward appearance of the brush, the best way is to compare it with Brewster's brush which one can observe by looking through certain minerals (pleochroic minerals: glaucophane, cordierite, etc.) and we refer to the excellent recent book by Können (1982, 1985) on the subject matter.

In 1949 Karl von Frisch discovered that many insects and, in particular, bees possess the ability to orient themselves using the distribution of polarization of the daylight to find their way, as well as to land on moving platforms (leaves, twigs, stems, blades of grass, etc.) under the most adverse weather conditions when direct access to sunlight is obscured.

Here, we should also recall that the Vikings, using the "findings stone" produced from some pleochroic mineral, were able to navigate in the absence of direct sunlight using the same natural effect, and thus, may have been some of the very first to utilize polarimetric effects in practice as early as the eighth century.

We have introduced this section on the visual observation of polarized light because from extended physiologic behavioral studies of the pertinent species of fish, insects and mammals we may be able to discern new improved design approaches for future polarimetric radar systems.

Chronological Table of the History of the Discovery of Polarization Leading to Radar Polarimetry

We consider it useful for the interested reader to reproduce and expand on the historical tables introduced by Gehreis (1974) and more recently updated by Können [1] with deletions and addition to meet historically important events leading to the development of radar polarimetry with which we will complete this paper.

HISTORY OF THE DISCOVERY OF POLARIZATION

- About 1000 The Vikings discovered the dichroic properties of crystals like corundum. With these crystals they observed the polarization of the blue sky and were thus able to navigate in the absence of the sun.
- 1669 Erasmus Bartholinus from Denmark discovered the double refraction of calcite crystals.
- 1690 Huygens discovered the polarization of the doubly-refracted rays of calcite. Without, however, being able to explain the phenomenon.
- 1808 Malus found the polarization of reflected light by using a calcite crystal as a filter. This filter apparently loses its double refraction when the entering light is polarized and the crystal is held in the correct position. Afterwards Malus formulated his law, which gives the relationship between the position of a polarizing filter and the quantity of transmitted light, when the entering light is totally (linearly) polarized.
- 1809 Arago rediscovered the polarization of the blue sky. In 1811 he discovered the optical activity of quartz, and in 1812 he constructed a filter out of a pile of glass sheets. In 1819 he found the polarization of comet tails and in 1825 the (weak) overall polarization of 22 degree haloes. In 1824 he found the polarization of the glow emitted by hot, incandescent metals. He was also the first to record the polarization of the moon.
- 1811 Biot discovered the polarization of the rainbow. In 1815 he established the optical activity of fluids such as turpentine, and in 1818 he studied the optical activity of gaseous turpentine in a gas column of 15 m length. Unfortunately, this apparatus exploded before he could finish his measurements. In 1815 Biot also discovered the strong dichroism of tourmaline.
- 1812 Brewster discovered the law, which was named after him, that indicates the relationship between the index of refraction and the angle of incidence at which light is totally converted by reflection into linearly polarized light. In 1818 he discovered Brewster's brush in pleochroic crystals.
- 1816 Fresnel gave a theoretical explanation of the existence of polarization.
- 1828 Nicol invented his prism, which can be considered to be the first easily usable polarizing filter.
- 1832 Faraday postulated the fundamental laws of electromagnetism.
- 1844 Haidinger found that the human eye has the ability to distinguish between unpolarized and polarized light, because in the latter case a yellowish figure appears on the retina (the Haidinger's brush).
- 1845 Faraday discovered the rotation of the polarization plane in magnetic fields.
- 1852 Stokes introduced the composition and resolution of streams of polarized, unpolarized and partially polarized light in terms of four parameters known as those of Stokes.
- 1872 Riemann introduced the transformation of mapping the sphere's surface onto the polar map.
- 1873 Maxwell succeeded in providing a rigorous formulation of the electromagnetic field equations derived from Faraday's postulates.
- 1874 Wright discovered the polarization of zodiacal light.
- 1878 Helmholtz introduced the vector decomposition into lamellar and rotational vector fields.
- 1882-3 Kirchhoff introduced the physical optics formulation of diffraction.
- 1884 Kiessling recorded that the glory is polarized.
- 1889 Cornu found that artificial haloes in sodium nitrate crystals are highly polarized because of the double refraction of the crystals.
- 1890 Lord Rayleigh explained the reason for the blue color of the sky.
- 1892 Poincare introduced the polarization sphere using the Riemann transformation and Stokes parameters.
- 1896 Sommerfeld introduced a rigorous theory of diffraction.
- 1905 Unov described the relationship between the degree of polarization of light reflected from rough surfaces and the albedo of the surface.
- 1911 Michelson discovered that certain beetles have a gloss which is circularly polarized.
- 1912 Sommerfeld introduces the Green's function formulation into diffraction theory.
- 1926 Stern and Gerlach discover the electron spin.
- 1926 Landau introduces the density matrix into quantum mechanics which is mathematically identical to the coherency matrix of polarization introduced by E. Wolf in 1959.
- 1926-9 Pauli introduces the spinor formalism into quantum mechanics.
- 1928 Land constructed his first polarizing filter. Further developments of this filter made it possible to study effects of polarization with a simple and efficient sheet filter. Such filters are also used in sunglasses, etc. to reduce the intensity of glare. Compared with the Nicol and other crystal filters used up to that point the development of this kind of sheet filter meant great progress.
- 1929 Wiener introduces the generalized harmonic analysis.
- 1932 Dirac introduced the (4 4) matrices named after him which were mathematically identical with Mueller polarization operators.
- 1933 Max Born published the first version of OPTIK.
- 1939 Le Grand and Kalle reported that scattered light underwater is polarized.

- 1940 Bridcard found that supernumerary rays shift when one looks at them through a linear filter which is then rotated.
- 1941 Jones introduces a new calculus for the treatment of optical systems based on Hans Mueller's polarimetric studies.
- 1947 Van de Hulst gave the first feasible explanation of the glory and explained its polarization directions.
- 1948 Sichak and Milazzo describe antennas for circular polarization.
- 1949 Yeh provides a first correct definition of polarization antenna power relations.
- 1949-50 Sinclair introduces the polarization scattering (RCS) matrix into radar.
- 1949 Kennaugh provides a first interpretation on circular polarization rain cancellation.
- 1949 Max von Frisch discovered that bees are more capable than man of distinguishing polarized from unpolarized light and use this ability to orientate themselves.
- 1951 (Booker/Rumsey/Deschamps/Kales/Bohnert) introduce techniques for handling elliptically polarized waves with special reference to antennas, Proc. IRE, Vol. 35 (May 1951).
- 1952 Kennaugh formulates his radar target characteristic operator theory based on his optimal polarization null concept.
- 1953 Deschamps introduces a hyperbolic protractor for microwave impedance measurements and other (polarization) purposes.
- 1954 Gent provides a polarimetric theory for radar target reflection.
- 1955 Shurcliff discovered that the human eye is also capable of distinguishing circularly polarized from unpolarized light.
- 1956 Graves introduced a radar polarization power scattering matrix.
- 1958 Duncan discovered the polarization of the aurora.
- 1959 Born and Wolf publish first edition of Principles of Optics based on Born's Optik (1933).
- 1959 E. Wolf introduces a rigorous derivation of the coherency matrix in the description of polarized fields.
- 1960 Copeland classifies (symmetrical) radar targets by polarization properties.
- 1960 Crispin et al describe the measurements and use of the radar scattering matrix.
- 1963 Beckmann and Spizzichino publish "The scattering of electromagnetic waves from rough surfaces".
- 1965 Lowenschuss describes radar scattering matrix applications.
- 1965 Bickel analyses some invariant properties of the polarization scattering matrix.
- 1965 IEEE Special Issue on "Radar Reflectivity", Aug. 1965.
- 1966 Fung introduces his first theory on scattering and depolarization of electromagnetic waves from a rough surface.
- 1966 Kanarevkin/Pavlov/Potekhin publish the polarization of radar signals (Russian).
- 1967 IEEE Proc., Special Issue on Partial Coherency, Jan. 1967.
- 1967 Hagfors describes a study of the depolarization of lunar radar echoes.
- 1967 Bolinder provides a geometrical analysis of partially polarized waves.
- 1968 Shup'yatskiy and Morgunov apply polarization methods to radar studies of clouds and precipitation.
- 1968 Beckmann publishes "The depolarization of electromagnetic waves".
- 1968 Kanarevkin/Potekhin/Shiskin publish "Maritime Polarimetry".
- 1968-71 McCormick and Hendry initiate their studies on polarization radar measurement of precipitation scattering.
- 1968 Crispin and Siegel publish "Methods of Radar Cross-Section Analysis", containing A.L. Maffet, "Scattering Matrices".
- 1970 Huynen defends his doctoral dissertation on a "Phenomenological Theory of Radar Targets".
- 1970 Thiel defends his dissertation on the presentation and transformation theory of quasi-monochromatic scattering in radio astronomy.
- 1971 Hendry and McCormick analyze polarization scatter properties of precipitation.
- 1971 Poelman provides performance evaluations of two polarization radar systems possessing linear (H,V) or circular (L,R) polarization antenna facility.
- 1973 Gehrels edited the first general source book on polarimetry.
- 1974 Gorshkov publishes "Ellipsimetry" (in Russian).
- 1975 Long publishes radar reflections from land and sea.
- 1975 Oguchi provides an in-depth analysis on "Rain Depolarization at cm/mm Wavelengths".
- 1975 Poelman reports on using orthogonally polarized returns to detect target echoes in Gaussian noise.
- 1975 Aboul-Atta and Boerner introduce a set of vectorial impedance boundary conditions for the natural dependence of harmonic polarimetric fields.
- 1976 Seliga and Brinzi suggest the potential use of radar differential reflectivity with measurements (Z_{CR}^0) at orthogonal polarizations for portraying precipitation parameters.
- 1976 Arpling and Eaves introduce the concept and design of the intrapulse polarization agile radar known as IPPAR.

- 1977 Metcalf assesses polarization diversity radar and radar technology in meteorological research.
- 1978 Ishimaru publishes "Wave Propagation and Scattering in Random Media".
- 1978 Boerner reports on polarization utilization in electromagnetic imaging.
- 1978 Silverman reports on chaff dispersion and polarization.
- 1979 Schneider and Williams provide an analysis on circular polarization in radar.
- 1979 IEEE Standard No. 1409-1979, "Test Procedures for Antennas".
- 1979 Ioannidis and Hammer analyze the optimum antenna polarization for target discrimination in clutter.
- 1979 Kozlov studies the radar contrast of two objects.
- 1981 Meischner and Schroth propose the design of an advanced polarization radar system for meteorological studies at DFVLR.
- 1982 Können publishes "Polarized Light in Nature" (in Dutch; English translation - 1985).
- 1985 Boerner edits the Proc. of a NATO-ARW on inverse methods in electromagnetic imaging with special emphasis on radar polarization.
- 1985 Collins publishes "Antennas and Radio Wave Propagation".
- 1985 Giuli analyses polarization diversity in radar.
- 1986 Kostinski and Boerner critically assess the fundamentals of radar polarimetry.
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CONCLUSIONS

It is impossible to provide here a satisfactory review on technological advances made in polarimetric radar electronics and we refer to recent state-of-the-art summaries of Giuli [18], Boerner [19] and Boerner and Kostinski [20]. A more elaborate and complete review including succinct mathematical, physical and signal processing aspects of radar polarimetry will be provided in the Proceedings of a forthcoming NATO-ARW-DIMRP 1987 [14].

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POLARIMETRIC RAIN BACKSCATTER MEASUREMENT MATRIX RADAR DATA BACKSCATTER MEASUREMENTS IN THE X- AND Q-BANDS

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ABSTRACT

This paper presents an evaluation of polarimetric backscatter measurements collected with coherent polarization radar systems in the X (8.9 GHz) and Q (14.1 GHz) bands, the first being operated in a cross-polarized and the second being a PM-CW system. The polarimetric measurement data consisted for each band of thirty files of time-sequential scattering matrix measurements expressed in terms of a linear (H,V) or circular polarization state basis. The rain backscatter takes place in a rain cell, defined by the raindrops and their large distances of 275 ft. (84 m) and 125 ft. (38 m), and the scattering matrices were measured far below the hydrometeor scattering center decorrelation time so that ensemble averaging of time-sequential scattering matrices may be applied. Radar data evaluation great care was taken in determining (i) polarimetric doppler velocities associated with the motion of descending caudate raindrops and of eddies within the moving swaths of coastal rain showers, and (ii) also the properties of the associated cross-polarization rain clutter nulls and their distributions on the Poincaré polarization sphere.

INTRODUCTION

During the past several years we at UIUC-EECS/AL have been involved in the persistent advancement of radar polarimetry and its applications to various disciplines including radar meteorology (1-11). Especially, we have advanced the fundamentals of radar polarimetry (4,5) and further developed Kennaugh's target characteristic operator theory (6,7) to the bistatic cases (8,9) and more recently applied the resulting target characteristic null max-polarization state theory of single scatterers (6,7,4,9) to the case of fluctuating distributed scatterers with applications to rain backscatter (10). In Agrawal & Kennaugh (10), we have developed a simplified descriptive theory of polarimetric (scattering matrix) backscatter from fluctuating distributed scatterers using (i) the coherency matrix and its properties, (ii) to formulate the Kennaugh target characteristic polarization theory for the time-dependent distributed scatterer case, and (iii) the Stogor-Pratt (12) model for describing the properties of descending raindrops.

In order to verify the rain backscatter model theory developed in Agrawal & Kennaugh (10), we were fortunate to be given pertinent polarimetric rain backscatter data (13-15) in the X- and Q-bands. Before we report the evaluation of these very exciting polarimetric rain backscatter data sets, we will first succinctly describe the polarimetric radar meteorological instrumentation set-up as well as the format of the polarimetric measurement files.

Radar Polarization Polarized Radar Meteorologic Instrumentation Facility at the O'Hare State Airport, and a few file links of (13, 14, 15)

The polarimetric rain backscatter radar data provided to us were collected by the RAC-KSC/UT-Radar Section (13,15) at the edge of the rain forest on the west coast of Washington State, USA along the Olympic Mountain range within a 50 miles from the Pacific Ocean, where the descending rain sheets of surface-based clouds and showers are typical. The radar system is a 100 MHz radar facility developed

by the RAC-KSC/UT-Radar Section is explained in greater detail in (13,14) and summarized in (11) and (16). The scattering matrices were measured for one pulse-gated measurement range cell with an X-band pulsed dual-polarization radar of linear (HV) antenna polarization state basis, transmitting pulses of 100ns width and with a pulse repetition frequency (PRF) of 5 KHz. The polarization state of the transmitted wave was switched electronically at 25 microseconds between the horizontal (H) and vertical (V) polarization states during the interval of successive pulses. The simultaneous reception of the returned wave in both the orthogonal co/cross-polarized channels for each of the two successive orthogonally polarized transmitted waves were then combined into one complete measurement of the scattering matrix $S(HV)$, assuming for the monostatic arrangement and reciprocal propagation conditions that $S_{HV} = S_{VH}$ (13,14) which needs further proof as discussed in Kostinski & Boerner (4).

For each X-hand data run, we were provided 50 files, each containing 2048 measurements spaced 400 microseconds apart for a total elapsed time of 0.8 seconds (13, 14,16). The acquisition of the individual scattering matrices was accomplished well below the decorrelation time of about 5.6 milliseconds (17). Together with the polarimetric scattering matrix data, meteorological ground truth and radar calibration information was supplied as described in more detail in (13) and (14).

Computer-Numerical Data Analyses

All data files provided to us on the rain backscatter data were analysed on our DEC-VAX 11/750 research computer and computer-graphics output was prepared for (i) the power spectra $|S_{HH}|^2$, $|S_{VV}|^2$, $|S_{HV}|^2$, $|S_{VH}|^2$, Span $[S]$, (ii) the mean COPOL/XPOL Null cluster mappings on the Aitoff-Hammer equal area projections (iii) the canting angle distribution, and (iv) the linear differential reflectivity Z_{DR} , the circular depolarization ratio (CDR) and the elliptic depolarization ratio (EDR) as defined in Agrawal (18), where some of the statistical evaluations compiled in more detail in (16), are interpreted.

Graphical Results and Identification of Important Observations

In our computer-numerical model verification (16), we found it most expedient to provide simultaneously (i) power spectral plots together with COPOL/XPOL Null cluster maps for all of the 50 data files of which we have selected one typical case for presentation in Fig. 1 (X-band) and Fig. 2 (Q-band).

From inspection of all of the 50 files (X-Q-bands), we observed that strong clustering of the clutter nulls occurs for strong backscatter signals whenever appreciable rain rates and relatively high wind velocities are prevalent, and that the spread about the mean clutter nulls increases either with decreasing rain rates which, in turn, produces decreasing return signals or with the creation of localized eddies which yet require more in-depth analyses. Associated with the clutter null clustering effect is the appearance of resonant peaks in the spectral power

shifts within the range of about 55 Hz to 245 Hz for the X-band pulsed radar and -400 Hz to -800 Hz for the Q-band CW radar, whereas the zero-frequency ground return peak is always present in all of the data files (both the X- and Q-band data), these off-zero resonance peaks occur only for higher rainrates and wind velocities, and are totally absent whenever the rain rate was very low, or whenever clear air conditions prevailed. It was also observed that at times more than one resonance peak appeared on either side of the zero ground return, and further more that the power spectral plots $|S_{HH}|^2$, $|S_{HV}|^2$ and $|S_{VH}|^2$ of varying fluctuation and widely non-uniformly distributed scatterers (with local velocity variances, etc.) can be rather different and not symmetrical about the zero ground reference frequency. This was not found to be the case for moving compact calibration test targets such as a sphere, corner reflector or top-hat for which all signatures were identical and similar to the symmetric span plots of fluctuating clutter (15). Thus, these polarimetric power spectral plots $|S_{HH}|^2$, $|S_{HV}|^2$ and $|S_{VH}|^2$ will contain very useful effective velocity information as was discussed for marine sea wave observations in Gleasing (19), and will provide a means of separating polarimetric Doppler signatures of relative slowly moving targets versus moving and fluctuating hydrometeor background clutter.

Physical Interpretation

It was shown that the clustering of the clutter nulls (CPOL Nulls close to circular and XPOL Nulls close to linear H and V polarization states on the Poincaré sphere) can be explained from our extended Stapor-Pratt rain model (11), showing in agreement with the available, though rather incomplete, meteorologic ground truth that slight canting of the ellipsoidal (oblate spheroidal) raindrops is prevalent with the average canting angle being rather constant $\psi = 15$ degrees (± 5 degrees), the observed resonance effects in the power spectral plots require a more diligent interpretation also because at X-band a coarse evaluation of the temporal power plots made us first anticipate that we are dealing with 60 Hz internal/external AC power supply harmonics or metal junction irradiation effects. Based on continuing rather elaborate power spectral analyses, we are proposing with confidence that instead of the 60Hz harmonics, the possible causes of the observed polarimetric power spectral resonances, which are closely associated and related to the localized CPOL/XPOL Null clutter clustering effects on the Poincaré sphere, could be either one or more of the following: (i) the uniform motion of in-phase descending raindrops within sheets of coastal rain showers moving in a fixed eastward direction with constant horizontal wind (shear) velocity gradient as was also observed by Gordon (20); (ii) the wind-driven in-phase oscillations of the descending rain drops within drifting rain swaths as was also observed by Warner and Rogers (21); Krehbiel and Beke (22); and/or (iii) Bragg-type scattering from turbulent eddies as was also observed by Gordon (23). Whereas the first model requires the existence of one set of distinct spectral off-zero frequency peaks, symmetrically spaced about the zero-frequency or zero clutter return peak, the second and third models will require multiple resonance peaks, i.e., in addition to the first also higher order harmonics will be present due to the resulting oscillations of the assumed fluctuating raindrop model and/or Bragg-type scattering from turbulent eddies.

The average Doppler velocity v observed within the fifty data files lie within $\pm 9m/s$ to $5m/s$ for first order resonances and about $4m/s$ to $15m/s$ for second order resonances, etc., using the Galilean approximation $\nu = \pm 2f v/c$ (24) for the observed frequency

shifts ($X(f_c = 9.375 \text{ GHz})$ band: $50 \text{ Hz} \leq \Delta f \leq 100 \text{ Hz}$) ($Q(f_c = 45 \text{ GHz})$ band: $250 \text{ Hz} \leq \Delta f \leq 1600 \text{ Hz}$), with c denoting the speed of light, the \pm sign indicating scatterer motion toward (+) and away from (-) the radar, and the ratio of the observed frequency shifts was within the expected range (18).

CONCLUSIONS

though the meteorologic ground truth provided was rather insufficient and the variance in wind velocity for rain rates and types of the measured precipitation events was not satisfactory (13,14,16), we nevertheless can state with confidence that polarimetric (scattering matrix) pulsed radar analyses of rain backscatter will provide a most welcome and additional tool for radar meteorology in that we will now be able to study dynamic changes of hydrometeor phase state transitions as we have shown in our analyses (18). In particular, the polarimetric Doppler processing of both the clutter null/max polarization states simultaneously with the power spectral returns should provide a means of distinguishing between polarimetric Doppler signatures resulting from various kinds of dynamically fluctuating hydrometeor scatterer motions, and at the same time also provides a means of obtaining instantaneous shape, size and material characteristics of the hydrometeor under investigation. Our observations were also found to be in agreement with more recent dynamic hydrometeor model theories developed by Metcalf (23) and co-workers (24). Further extensions and integrations of these with our models toward the derivation of other clutter types such as dynamic rough terrain/surface with top/sub-surface layers of volumetric scatterers can now straight-forwardly be deduced.

However, in order to advance simultaneously the underlying theory, metrology and clutter descriptive algorithm development, we urgently require (i) a rapid advancement in the design and manufacture of polarimetric (scattering matrix) pulsed radar system covering the meter to sub-millimeter wavelength region (16,18), and (ii) very considerable improvement in more exact remote probing instrumentation of instantaneous hydrometeor ground clutter within the measurement range bin and surrounding meteorological conditions as proposed in (16). A first encouraging although still very small step in this direction (25) has been achieved by the acquisition and installation of the DISTR multi-function polarimetric C-band radar meteorological instrumentation facility at Oberpfaffenhofen, FRG as was reported during the recent 23rd Conference on Radar Meteorology, 1986 Sept. 22-26, Snowmass, Colorado, USA (26,27,28).

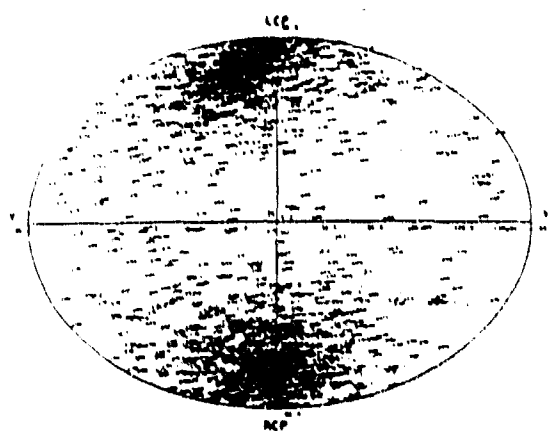
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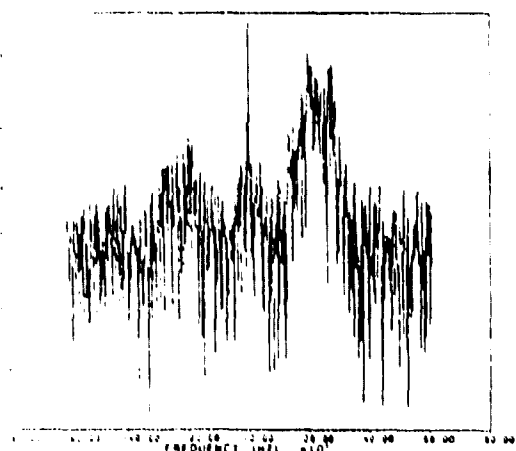
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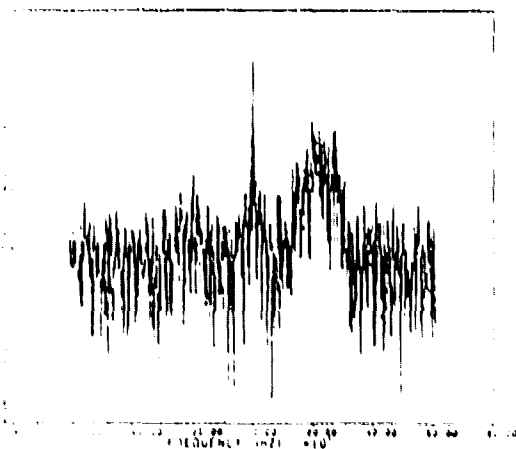
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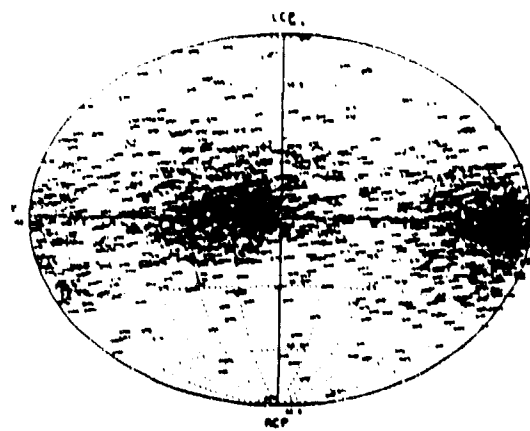
COPOL Nulls



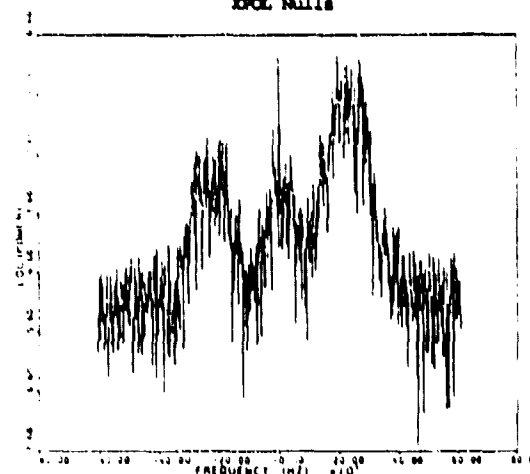
Power Spectrum (HB)



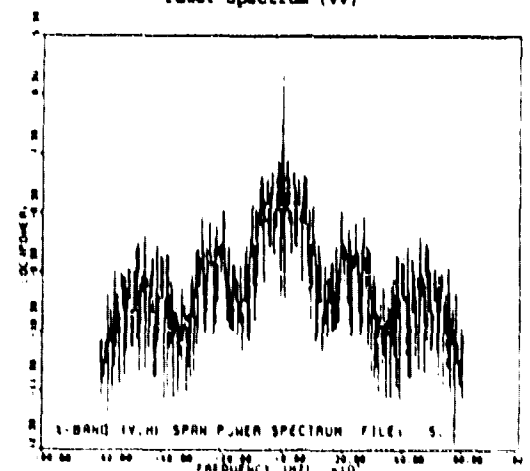
Power Spectrum (HV)



XPOL Nulls



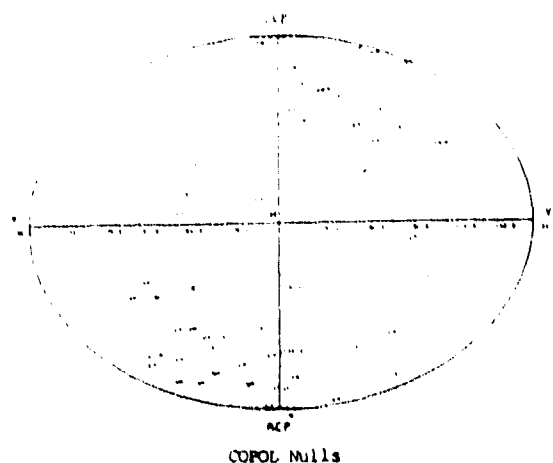
Power Spectrum (VW)



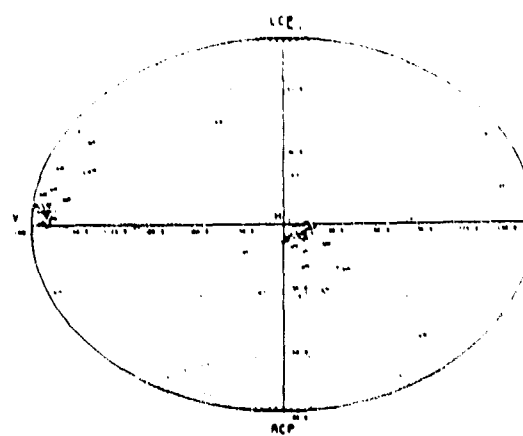
Power Spectrum Span (V, H)

Fig. 1: Clutter COPOL/XPOL Null and power spectral plots for the data file 5

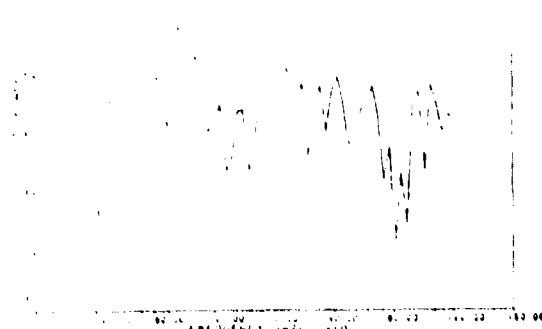
| | | |
|------------------------------|------------------------|---------------|
| Frequency X-Band, | Date 19-FEB 85, | Time 12:06:04 |
| Trailer Heading (deg) 270.0, | Wind vel. (m/s) 2.8, | |
| Wind Dir. (deg) 318.1, | Pressure (m/b) 999.1, | |
| Temp. (C) 5.4, | Dew point (C) -15.6, | |
| Tip Rate (mm/hr) 8.9, | Drip Rate (mm/hr) 14.6 | |



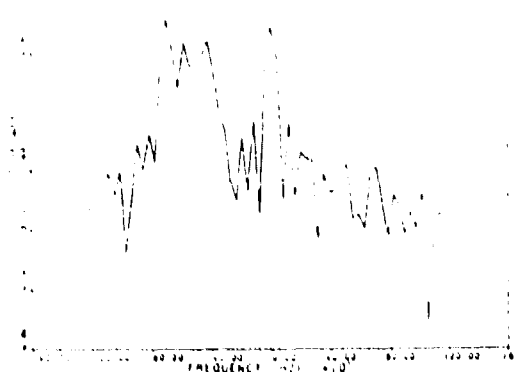
COPOL Nulls



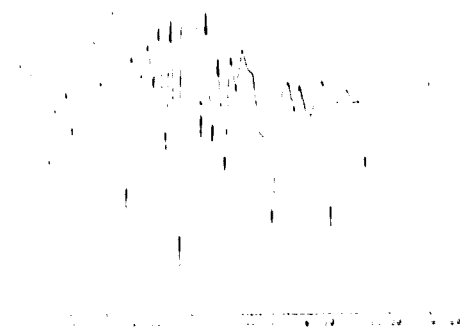
XPOL Nulls



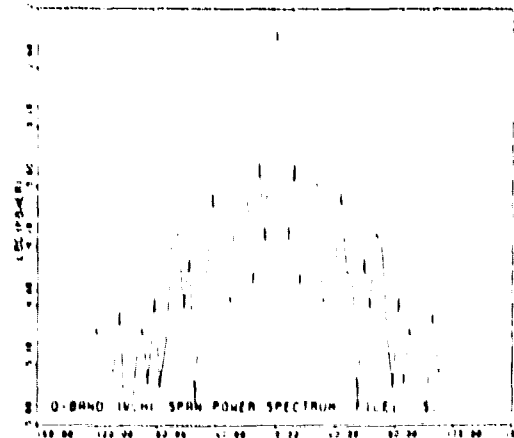
Power Spectrum (HH)



Power Spectrum (VV)



Power Spectrum (HV)



Power Spectrum Span (V,H)

Fig. 2: Clutter COPOL, XPOL Null and power spectral plots for the data file 5

| | | |
|------------------------------|----------------------|---------------------------|
| Frequency Q-Band. | Date 19-FEB-85. | Time 12:05:04 |
| Trailer Heading (deg) 270.0. | Wind vel. (m/s) 2.8. | Pressure (m.b) 999.3. |
| Wind Dir. (deg) 310.1. | Temp. (C) 5.4. | Dew point (C) -15.6. |
| Rip Rate (mm/hr) 8.9. | | Drizzle Rate (mm/hr) 14.6 |

ADVANCED RADAR POLARIMETRY, RADAR CROSS SECTION
MATRIX MEASUREMENTS, AND RADAR ABSORBING MATERIALS

OUTLINE OF AGARD - SHORT COURSE LECTURE SERIES
By Dr. Wolfgang-M. Boerner, Professor, UIC-EECS/CL

WHO SHOULD ATTEND

People from industry, research organizations, universities, and governmental/-military authorities who are involved in the development, manufacture, control, or utilization, and application of advanced dual polarization radar/-scatterometer/radiometry systems in surveillance, impact avoidance, seeker, search, fire control modes of operation.

BACKGROUND REQUISITES

Attendees should have some background knowledge in applied mathematics, electromagnetic theory, electromagnetic wave propagation, diffraction & scattering, and be familiar with basic radar imaging concepts at a level of at least the M.Sc. (Physics, Electromagnetic Wave Engineering, Radar) degree.

SEMINAR OBJECTIVE

Radar polarimetry is becoming of increasingly higher importance in high frequency (m-to-sub-mm-wave) high resolution radar target imaging, clutter analysis, and target in clutter detection. Similarly, such fields as radar meteorology, remote sensing, sea/coastal environment surveillance heavily rely upon a thorough understanding of the polarization state transformation properties of isolated and distributed scatterers.

This course presents the principles of modern techniques for high resolution polarimetric radar target in clutter detection/ classification/ imaging and identification of low RCS targets produced from multi-layered, isotropic and anisotropic radar absorbing materials.

Lecturer

Dr. Wolfgang-M. Boerner
Professor & Director
1-(312)-996-5480/5140

University of Illinois at Chicago
EECS/Communications Laboratory (m/c 154)
840 W. Taylor Street, SEL - 4210
Chicago, IL USA-60680-4348

Language

English

CONTACT

Dr. Jean-Paul Marcellin,
Chief, Radar Signatures/Measurements
Radar Division
ONERA, 29, Avenue de la Div. LECLERC,
F-92320 CHATILLON/BAGNEUX, France
(011) 33.1.46.57.11.60

Lecture Material

Each attendant will be provided with detailed course material accompanying the lectures to be distributed well in advance by Dr. J.-P. Marcellin.

Lecture Series Outlines

Monday, May 04, 1987

Registration: 8:00 to 9:00 AM

INTRODUCTION

Overview - Radar Polarimetry: An Integrated
Field of Electromagnetic Inverse Scattering

Morning
(9:00 to 12:00)

- The electromagnetic inverse problem and its relationship to other inverse problems in sonar, seismology, non-material testing, radiology and astronomy.
- The vector inverse problem and the radar target imaging approach

Fundamentals of Electromagnetic Wave Propagation/Diffraction/Scattering

Afternoon
(13:00 to 17:00)

- The electromagnetic wave and the polarization spinor/vector
- Basics of radar target scattering: The RCS in the low/resonance/physical optics/-geometrical optics region
- The monostatic and bistatic electromagnetic inverse problems in radar target imaging

Tuesday, May 05, 1987

Fundamentals of Radar Polarimetry: Part I - The Coherent Case

Morning
(8:00 to 12:00)

- Polarization state description
- The coherent target scattering matrices
- The three-stage polarimetric target identification problem
- The target operator/scattering matrix and its properties
- The received voltage optimization problem
- The polarization fork and its proper interpretation
- Other target characteristic operators

Fundamentals of Radar Polarimetry: Part II - The Incoherent Case

Afternoon
(13:00 to 17:00)

- Partially polarized waves
- The coherency matrix, the Stokes vector
- The Stokes reflection and Mueller matrices
- The average Mueller matrix and the Radar scattering matrix
- Clutter descriptive theories

Lecture Series Outlines, cont'd.

Wednesday, May 06, 1987

Fundamentals of Radar Polarimetry:

Part III - The Inverse Problem/Signal Processing

Morning
(8:00 to 12:00)

- Coherent polarimetric target imaging
- The target vs. clutter signal optimization problem
- The down/cross/volumetric range polarimetric high resolution radar imaging approach

Fundamentals of Radar Polarimetry:

Part IV - Polarization Radar Metrology

Afternoon
(13:00 to 17:00)

- Basic RCS matrix measurement procedures
- Basic Polarization Radar calibration tests
- Monostatic scattering matrix measurements
- Multistatic scattering matrix measurements
- Groundtruths Acquisition

Thursday, May 07, 1987

Applications of High-Resolution Radar Polarimetry

Morning
(8:00 to 12:00)

- Scattering matrix algorithm design
- Surveillance radar
- Imaging radar
- Fire control radar
- Other radar applications
- Polarimetric scatterometry and radiometry

Afternoon
(13:00 to 16:00)

Panel Discussion and Conclusion

(Adjournment: 16:00 PM)



Carl-Cranz-
Gesellschaft e.V.

Lehrgangszentrum
Oberpfaffenhofen

Society for Engineering and Scientific Education

Prof. Boerner

Lecture S2.19

New Course

Advanced Radar Polarimetry and its Applications

27.9. - 29.9.1988 in Oberpfaffenhofen

Who should attend

People from industry, research organizations, universities, and governmental/military authorities who are involved in development, manufacture, control or utilization, and application of advanced dual polarization radar/scatterometer/radiometry systems in surveillance, impact avoidance, seeker, search, fire control radar modes of operation

Seminar Objectives

Radar polarimetry is becoming of increasingly higher importance in high frequency (m-to-sub-mm-wave) high resolution radar target imaging, clutter analysis, and target in clutter detection. Similarly, such fields as radar meteorology, remote sensing, sea/coastal environment surveillance heavily rely upon a thorough understanding of the polarization state transformation properties of isolated and distributed scatterers.

This course presents the principles of modern techniques for high resolution polarimetric radar target in clutter detection/classification/imaging and identification.

Lecturers

Dr. Wolfgang-M. Boerner
Dr. Alexander B. Kostinski

Communications Laboratory, Department of
Electrical Engineering & Computer Science,
University of Illinois at Chicago, USA

Dr. Richard Huynen

P.Q. Research
Los Altos Hills, CA, USA

Language

English

Seminar Outline**Tuesday, Sept. 27**

Boerner

Overview - Radar Polarimetry: An Integrated Field of Electromagnetic Inverse Scattering

- The electromagnetic inverse problem and its relationship to other inverse problems in sonar, seismology, non-material testing, radiology and astronomy
- The vector inverse problem and the radar target imaging approach

Kostinski
Huynen**Fundamentals of Electromagnetic Wave Propagation/Diffraction/Scattering**

- The electromagnetic wave and the polarization spinor/vector
- Basics of radar target scattering: The RCS in the low/resonance/physical optics/geometrical optics region
- The monostatic and bistatic electromagnetic inverse problems in radar target imaging

Wednesday, Sept. 28Kostinski
Huynen**Fundamentals of Radar Polarimetry:
Part I - The Coherent Case**

- Polarization state description
- The coherent target scattering matrices
- The three-stage polarimetric target identification problem
- The target operator/scattering matrix and its properties
- The received voltage optimization problem
- The polarization fork and its proper interpretation
- Other target characteristic operators

Kostinski
Huynen**Fundamentals of Radar Polarimetry:
Part II - The Incoherent Case**

- Partially polarized waves
- The coherency matrix, the Stokes vector
- The Stokes reflection and Mueller matrices
- The average Mueller matrix and the radar scattering matrix
- Clutter descriptive theories

Thursday, Sept. 29

Boerner
Kostinski

**Fundamentals of Radar Polarimetry:
Part III - The Inverse Problem**

- Coherent polarimetric target imaging
- The target vs. clutter signal optimization problem
- The down/cross/volumetric range polarimetric high resolution radar imaging approach

Huynen

Target Parameter Evaluation, (a) new sampling methods, (b) surface torsion and phyllotaxis, (c) target decomposition

Boerner

The Polarimetric Matched Filter Concepts in POL-SAR Imaging
Adjournment

Material

Each attendant will be provided with detailed course material accompanying the lectures.

Background Requisites

Attendees should have some background knowledge in applied electromagnetic theory, electromagnetic wave propagation, diffraction & scattering, and be familiar with basic radar imaging concepts.

Organization

Location

D-8031 Wessling-Oberpfaffenhofen (ca. 25 km west of Munich), Flugplatz, Phone (08153) 28-444

Course Schedule: Tuesday 08.45 - 17.00 h
 Wednesday - Thursday 09.00 - 17.00 h

Fee

DM 1.080.--

Members of CCG DM 970.--

Members of German universities may get a reduction on request.

Please note, that in case of a cancellation of a confirmed registration, a processing fee will be charged as follows: DM 50.-- until 7 days before the course, 25 % of the course fee if later.

Registration and Room Reservations

Please write to Carl-Cranz-Gesellschaft e.V., Flugplatz, D-8031 Wessling-Oberpfaffenhofen, or call phone Nr. (08153) 28-413, Telex: 526419 dvlop d. A shuttle service is offered for participants without a car.

Organization

Oberst a.D. Kurt Hofmann, Carl-Cranz-Gesellschaft e.V., Oberpfaffenhofen, Phone (08153) 28-444

Scientific Coordination

Dr. Arno Schroth, DFVLR, Institut für Hochfrequenztechnik, Phone (08153) 28-325

HOW TO GET TO CCG

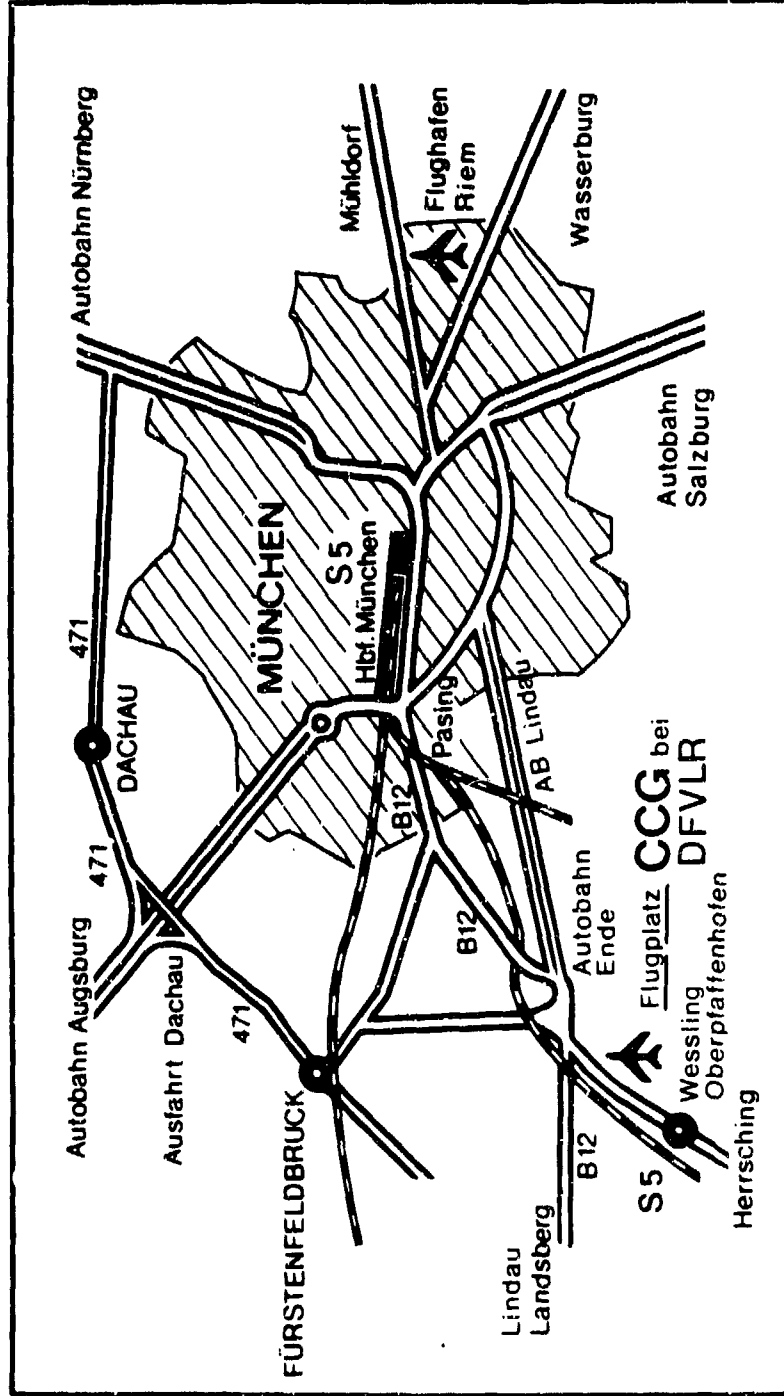
BY AIR: Airport Munich (Riem) - Take Airport-Bus to Main Railroad Station - Take Commuter Train (S-Bahn S5) to "Herrsching" - Leave at "Wessling" (42 minutes from Main Railroad Station to Wessling)

BY TRAIN: From Munich Main Railroad Station take "S-Bahn" (S5) as above

BY CAR: From Wessling you may call CCG (Phone: 28 444) to be picked up - Walking distance is 25 minutes.

If you get lost: Please call 08153 28 444

M A P CCG WESSLING - OBERPFAFFENHOFEN



TECHNICAL PROGRAM OUTLINE

NATO-ARW-DIMRP '88

on

DIRECT & INVERSE METHODS IN RADAR POSITIONING

Kur und Kongress-hotel Residence
Bad Windsheim, FRG, September 18-24, 1988

(1988 June 30)

Official Language: ENGLISH

SUNDAY, 18 SEPTEMBER 1988

10:00 to 12:00 - WORKSHOP DIRECTORS' MEETING (Room A)

Director: WOLFGANG-M. BOERNER, UIC, Chicago, USA

Co-Directors: HANS BRAND, Univ. Erlangen-Nürnberg, FR Germany
LEONARD A. CRAM, THORN-EMI, Wells, Somerset, England
DINO GIULI, Univ. of Florence, Italy
DAG T. GJESSING, NTNF, Kjeller, Norway
WILLIAM A. HOLM, GIT-RAIL, Atlanta, USA
WOLFGANG KEYDEL, DFVLR, Oberpfaffenhofen, FR Germany
ERNST LÜNEBURG, DFVLR, Oberpfaffenhofen, FRG
YASUMITSU MIYAZAKI, USTT, Toyohashi, Japan
FREDERIC MOLINET, Soc. Moth., Plessis-Robinson, France
MARTIN VOGEL, DFVLR, Oberpfaffenhofen, FR Germany
WERNER WIESBECK, TUK, Karlsruhe, FR Germany

1200 to 13:00 - LUNCH BREAK

13:00 - DEPARTURE OF WORKSHOP BUS "ARW-DIMRP-KUK, BAD WINDSHEIM," from Frankfurt Airport Bus Station (opposite Main Arrival Hall B - lower level): see Travel Instructions, Travel Questionnaire, and Terminal Guide Map

14:00 - DEPARTURE OF WORKSHOP BUS "ARW-DIMRP-KUK, BAD WINDSHEIM," from Nuremberg Central Station (main station exit towards city: Bahnhofsplatz): see Travel Instructions and Travel Questionnaire

14:30 to 18:30 - REGISTRATION AND RECEPTION (Foyer of Congress- Center and Rm. A)

DR-ING. GERT SCHALLER, UEN, Erlangen, FRG
FRAU MARGARETE GEIGER, UEN, Erlangen, FRG
DR-ING. SIEGFRIED OSTERRIEDER, GHS, Ravensburg, FRG
MR. NABIL SOLIMAN, UIC, Chicago, IL./USA
MR. BRIAN D. JAMES, UIC, Chicago, IL./USA
DR-ING. HELMUT SÜSS, DFVLR, Oberpfaffenhofen, FRG
DR-ING. KARL TRAGL, DFVLR, Wessling/OPH, FRG

17:30 to 19:00 - BUFFET

Hosts: HERR ROLF K. ERLNBACH, KuK Hotel, Manager
FRAU JUTTA BROCKHOFF, KuK Hotel, Vice-Manageress

NOTE: PROGRAM CHANGES ARE CONTAINED IN FINAL TECHNICAL PROGRAM OUTLINES: 1988 Sept. 15

- 20:00 to 21:45 - **OPENING SESSION (O)**
 Chairman: PROF. DR. DAG T. GJESSING
 Norges Teknisk-Naturvitenskapelige Forskningsrad, Kjeller
 and University of Tromsø, Tromsø, Norway
- 20:00 - **OPENING REMARKS**
 DR. MARTIN VOGEL, DFVLR, Oberpfaffenhofen, FRG
- 20:10 - **INTRODUCTION OF DIRECTORS AND GUESTS OF HONOR**
 MR. LEONARD A. CRAM, THORN-EMI, Wells, UK
- 20:20 - **WELCOME ADDRESS BY HOST INSTITUTE**
 DR. WOLFGANG KEYDEL, DFVLR, Oberpfaffenhofen, FRG
- 20:30 - **TECHNICAL PROGRAM DESCRIPTION**
 O-1*: Historical Development of Radar Polarimetry - Unresolved Problems
 Incentives for this Workshop
 PROF. WOLFGANG-M. BOERNER, UIC-EECS, Chicago, IL./USA
- 20:40 - **OPENING LECTURE**
 O-2*: **POLARIZATION IN NATURE**
 DR. GÜNTER P. KÖNNEN
 K.N.N.I. deBilt, Utrecht, NL
- 21:30 - **SPOUSES' TOUR AND CULTURAL PROGRAM DESCRIPTION**
 DR-ING. GERD SCHALLER, UEN, Erlangen, FRG
 DR-ING. HELMUT SÜSS, DFVLR, Oberpfaffenhofen, FRG
- 21:45 - **GREETINGS AND WISHES FOR A SUCCESSFUL WORKSHOP**
 MR. ROLF K. ERLÉNACH, KUK Hotel Manager
 FRAU JUTTA BROCKHOFF, KUK Hotel Vice-Manager
- 22:00 - **DAY'S END: "Hotel at Rest"**
 (See information on KUK Hotel Residenz Workshop Arrangements Noise)
- * all numbered presentations will appear as papers in the Workshop Proceedings

MONDAY, 19 SEPTEMBER 1988

- 6:00 - **MORNING CALL**
 6:45 to 7:45 - **BREAKFAST**

SESSION I

- 8:00 to 10:00 - **BASIC POLARIZATION THEORY**
 Chairman: DR. FREDERIC MOLINET
 Société Mothesim, Le Plessis-Robinson, France
- 8:00 - I-1: **Definitions of Polarization in Radar**
 PROF. HAROLD MOTT
 Univ. of Alabama, University, AL/USA
- 8:30 - I-2: **The Jones Vector and the Stokes Vector: Coherent Versus Partially Coherent Wave Treatments**
 PROF. RASHEED M.A. AZZAM

18:45 to 21:45 - VISIT OF DOWNTOWN BAD WINDSHEIM AND RECEPTION AT CITY HALL

18:45 - DEPARTURE WITH GUIDE FROM KUK HOTEL

20:00 - ARRIVAL AT CITY HALL

20:15 - RECEPTION BY FIRST MAYOR AT THE HISTORICAL CITY HALL CHAMBER

21:00 - RETURN TO HOTEL OR VISIT TO LOCAL PUBS

22:00 - DAY'S END: "HOTEL AT REST," (NOISE!)

TUESDAY, 20 SEPTEMBER 1988

6:00 - MORNING CALL

6:45 to 7:45 - BREAKFAST

SESSION IV

8:00 to 10:00 - POLARIMETRIC RADAR METROLOGY

Chairman: MR. JERRY EAVES
GIT-RAIL, Atlanta, GA/USA

8:00 - IV-1: Polarization Scattering Matrix Measurements Using Near/Far Field Ranges

DR. JONATHAN D. YOUNG
DR. ERIC WALTON
Ohio State U., Electro-Science Lab., Columbus, OH/USA

8:30 - IV-2: Polarization Purity in Microwave Scattering Matrix Measurements

PROF. ANDREW BLANCHARD
PROF. ADRIAN K. FUNG
University of Texas at Arlington, Arlington, TX/USA

8:50 - IV-3: Polarization Scattering Matrix Measurements on Outdoor Ranges

DR. BERND RÖDE
DR-ING. REINHARD HAMMEL
DFVLR-NE-HF, Oberpfaffenhofen, FR Germany

9:10 - IV-4: Polarimetric Measurements of m-to-mm Wave Propagation Path Effects

DIPL-ING. EGON PETER BAARS
DR-ING. EBERHART HANLE
FHP/FGAN, Wachtberg-Werthhoven, FR Germany

9:30 - IV-5: Polarimetric Target and Clutter Scattering Matrix Measurements at mm-to-sub-mm Wavelengths

DR. JERRY JEPPE
DR. COLLIN SILLENCE
Radar Electronics Div., THORN-EMI,
Wells, Somerset, England, UK

10:00 to 10:30 - COFFEE BREAK

SESSION V

10:30 to 12:30 - CALIBRATION OF POLARIMETRIC RADAR AND POL-SAR SYSTEMS

University of New Orleans, New Orleans, LA/USA

- 9:00 - I-3: Fundamental Equations of Radar Polarimetry
DR. ALEXANDER B. KOSTINSKI
WOLFGANG-M. BOERNER
UIC-EECS/CL, Chicago, IL/USA
- 9:30 - I-4: An Alternative Approach to Radar Polarimetry
DR. ZBIGNIEW H. CZYZ
Przemystowy Instytut Telekomunikacji, Warszawa, Poland
- 10:00 to 10:30 - COFFEE BREAK

SESSION II

- 10:30 to 12:30 - FOUNDATIONS OF RADAR POLARIMETRY
Chairman: PROF. ADOLF LOHMANN
UEN, Erlangen, FR Germany
- 10:30 - II-1: Polarimetric Target Decomposition Theory
DR. J. RICHARD HUYNEN
P.Q. Research, Los Altos Hills, CA/USA
- 11:00 - II-2: Optimal Reception of Partially Polarized Waves
DR. ALEXANDER B. KOSTINSKI
MR. BRIAN D. JAMES
PROF. WOLFGANG-M. BOERNER
UIC-EECS/CL, Chicago, IL/USA
- 11:30 - II-3: Uniqueness of Decomposition Theories in Radar Target Analysis
DR. SHANE R. CLOUDE
Univ. of Dundee, Dundee, Scotland, UK
- 12:00 - II-4: Polarization Radar Signal Description: Modeling
and Processing of Polarimetric Pulse Radar Data
DR-ING. GERD WANIELIK
AEG-Telefunken Al, Ulm/Donau, FR Germany
- 12:30 to 13:45 - LUNCH BREAK

SESSION III

- 13:45 to 15:25 - POLARIMETRIC RADAR CONCEPTS
Chairman: PROF. WERNER WIESBECK
Technical University Karlsruhe, Karlsruhe, FRG
- 13:45 - III-1: Basic Polarimetric Signatures of Targets and Clutter
DR. WILLIAM A. HOLM
Georgia Inst. of Technology, RAIL Atlanta, GA/USA
- 14:15 - III-2: Inverse GTD via Polarimetric Linear Prediction
PROF. HEINZ CHALOUPKA
University Wuppertal, Wuppertal, FR Germany
- 14:35 - III-3: Specular Target Geometry and Scattering Matrices
PROF. BING-YUEN FOO

DePaul University, Chicago, IL./USA
PROF. SUJEET K. CHAUDHURI
Univ. of Waterloo, Waterloo, ONT/Canada
PROF. WOLFGANG-M. BOERNER
UIC-EECS/CL, Chicago, IL/USA

14:55 - III-4: The Theory and Measurement of Surface Torsion
DR. RICHARD J. HUYNEN
P.Q. Research, Los Altos Hills, CA/USA

15:15 to 15:45 - TEA BREAK

MEETING WDG-1

15:45 to 17:45 - WORKING DISCUSSION GROUP(S) MEETING

Chairman: MR. LEONARD A. CRAM
THORN-EMI, Wells, Somerset, England, UK

15:45 - ORGANIZATION OF WORKING DISCUSSION GROUPS

PROF. WOLFGANG-M. BOERNER
UIC-EECS/CL, Chicago, IL/USA

15:55 - INTENT, PURPOSE, AIM OF WORKING DISCUSSION GROUP MEETINGS

DR. DAG T. GJESSING
Norges Teknisk-Naturvitenskapelige Forskningsrad, Kjeller

16:05 - GUIDELINES FOR PREPARATION OF WORKING DISCUSSION GROUP REPORTS

DR. ERNST LÜNEBURG
DR. MARTIN VOGEL
DFVLR, Oberpfaffenhofen, FR Germany

16:15 - SEPARATION INTO SIX SPECIFIC WORKING DISCUSSION GROUPS AND DISTRIBUTION OF QUESTIONNAIRES AND ADDITIONAL INFORMATION (see details in "Information on Working Group Discussion...")

W-1: Assessment of Literature on Polarimetric Theory & Applications

Coordinators: G. Wanielik and V.N. Bringi

W-2: Polarimetric Target and Clutter Analyses: (Direct Scattering)

Coordinators: J. Hjelmstad and Y.M.M. Antar

W-3: Polarization Diffraction Tomography: Sensing of Concealed Objects

Coordinators: H. Blok and H. Hellsten

W-4: Unification of Nomenclature, Conventions & Standards in POL-RAD/SAR/ISAR Imaging

Coordinators: A. Blanchard and D. Stock

W-5: Processing, Formatting & Calibration of POL-RAD/SAR/ISAR Measurements

Coordinators: J. van Zyl and G.A. Mueller

W-6: Acceleration of Int'l/NATO Interaction: Design of INT-NATO POL-RAD/SAR Measurement Campaigns (Administrative)

Coordinators: J.G. Smith and J.L. Eaves

17:45 - ADJOURNMENT

17:50 to 18:40 - SUPPER

18:45 to 21:45 - VISIT OF DOWNTOWN BAD WINDSHEIM AND RECEPTION AT CITY HALL

18:45 - DEPARTURE WITH GUIDE FROM KUK HOTEL

20:00 - ARRIVAL AT CITY HALL

20:15 - RECEPTION BY FIRST MAYOR AT THE HISTORICAL CITY HALL CHAMBER

21:00 - RETURN TO HOTEL OR VISIT TO LOCAL PUBS

22:00 - DAY'S END: "HOTEL AT REST," (NOISE!)

TUESDAY, 20 SEPTEMBER 1988

6:00 - MORNING CALL

6:45 to 7:45 - BREAKFAST

SESSION IV

8:00 to 10:00 - POLARIMETRIC RADAR METROLOGY

Chairman: MR. JERRY EAVES
GIT-RAIL, Atlanta, GA/USA

8:00 - IV-1: Polarization Scattering Matrix Measurements Using Near/Far Field Ranges

DR. JONATHAN D. YOUNG
DR. ERIC WALTON
Ohio State U., Electro-Science Lab., Columbus, OH/USA

8:30 - IV-2: Polarization Purity in Microwave Scattering Matrix Measurements

PROF. ANDREW BLANCHARD
PROF. ADRIAN K. FUNG
University of Texas at Arlington, Arlington, TX/USA

8:50 - IV-3: Polarization Scattering Matrix Measurements on Outdoor Ranges

DR. BERND RÖDE
DR-ING. REINHARD HAMMEL
DFVLR-NE-HF, Oberpfaffenhofen, FR Germany

9:10 - IV-4: Polarimetric Measurements of m-to-mm Wave Propagation Path Effects

DIPL-ING. EGON PETER BAARS
DR-ING. EBERHART HANLE
FHP/FGAN, Wachtberg-Werthhoven, FR Germany

9:30 - IV-5: Polarimetric Target and Clutter Scattering Matrix Measurements at mm-to-sub-mm Wavelengths

DR. JERRY JEPPI
DR. COLLIN SILLENCE
Radar Electronics Div., THORN-EMI,
Wells, Somerset, England, UK

10:00 to 10:30 - COFFEE BREAK

SESSION V

10:30 to 12:30 - CALIBRATION OF POLARIMETRIC RADAR AND POL-SAR SYSTEMS

Chairman: DR. HANS-PETER SCHMID
General-Dynamics, Pomona, CA/USA

- 10:30 - V-1: Assessment of Calibration Procedures for Polarimetric Radar Systems
MR. LLOYD W. ROOT
US Army Missile Command, Redstone Arsenal, AL/USA
- 11:00 - V-2: Understanding Reciprocity in Radar Polarimetry
DR. MATTHEW FEINSTEIN
The John Hopkins University, Applied Physics Laboratory,
Laurel, MD/USA
- 11:20 - V-3: Calibration of Scattering Matrix Radar Measurements
DR. ADRIAN BRITTON
DR. GRAHAM CRISP
DR. ALEC DEADMAN
Polarimetric Radar Section, Electronics Division
RSRE, Great Malvern, England, UK
- 11:40 - V-4: Calibration of Broadband Polarimetric Radar Imaging Systems
DR. HENDRIK VAN BRUNT
MR. DONALD R WEHNER
Naval Ocean Systems Center, San Diego, CA/USA
- 12:00 - V-5: Pre/Inflight/Post-Calibration of Polarimetric Synthetic Aperture
Radar (POL-SAR) Systems: Polarimetric Calibration and Remote Sensing
Applications Using an X-C-L Band POL-SAR System
DR. ROBERT A. SHUCHMAN
DR. DAN R. SHEEN
Environmental Research Laboratory, ERIM, Ann Arbor, MI/USA

12:30 to 13:45 - LUNCH BREAK

SESSION VI

- 13:45 to 15:15 - POLARIMETRIC SIGNAL PROCESSING
Chairman: PROF. ALFONSO FARINA
Selenia, S.P.A., Rome, Italy
- 13:45 - VI-1: Polarimetric Signal Processing Techniques
PROF. DINO GIULI
DR-ING. MONICA GHERADELLI
University of Florence, Florence, Italy
- 14:15 - VI-2: Multispectral Polarimetric Radar Signal Processing: Performance
Evaluation of Polarimetric Signal Algorithms
DR. KENNETH C. STIEFVATER
Rome Air Development Center, Griffis AFB, NY/USA
- 14:35 - VI-3: Polarimetric Signal Processing in Radar Target Versus Clutter
Separation
DR. DONALD E. STOCK
Radar Systems Div., AEG/AG, Ulm, FR Germany
- 14:55 - VI-4: Polarimetric Signal Processing in Δk -Pulse Polarimetric Scatterometry
DR-ING. JENS HJELMSTAD
DR. DAG T. GJESSING
NINF--PFM, Kjeller, Norway

15:15 to 15:45 - TEA BREAK

MEETING WDG-2

15:45 to 17:45 - WORKING DISCUSSION GROUP ACTIVITIES (W-1 TO W-6)
(Discussion within Individual Groups)

17:45 - ADJOURNMENT

17:50 to 18:40 - SUPPER

18:45 to 21:00 - VISIT TO DOWNTOWN BAD WINDSHEIM AND ORGAN RECITAL AT ST. KILIAN

19:00 - DEPARTURE WITH GUIDE FROM KUK HOTEL

19:50 - ARRIVAL AT BAROQUE RENAISSANCE CHURCH, ST. KILIAN

20:00 - GUIDED TOUR THROUGH HISTORICAL CHURCH (GUIDE: MRS. LORENZ)

20:20 - ORGAN RECITAL (WORKS BY J.S. BACH, C. FRANK, D. BUXDEHUDE and J. FACHELBEL)
ORGANIST: KANTOR UHLMANN.

21:20 - RETURN TO HOTEL OR VISIT OF LOCAL PUBS

22:00 - DAY'S END, "HOTEL AT REST," (NOISE!)

WEDNESDAY, 21 SEPTEMBER 1988

6:00 - MORNING CALL

6:45 to 7:45 - BREAKFAST

SESSION VII

8:00 to 10:00 - VECTOR (POLARIZATION) DIFFRACTION TOMOGRAPHY

Chairman: PROF. DR. MANFRED PFEILER
Siemens AG, MTB, Erlangen, FR Germany

8:00 - VII-1: Vector (Polarization) Diffraction Tomography
PROF. DR. ANTHONY J. DEVANEY
Northeastern University, Boston, MA/USA

8:30 - VII-2: Toward a Unified Theory of Vector Diffraction Tomography
PROF. KARL J. LANGENBERG
University of Kassel, Kassel, FR Germany

9:00 - VII-3: Assessment of Resolution and Image Quality in Microwave Diffraction
Tomography
DR. DOMINIQUE LESSELIER
PROF. WALID TABBARA
PROF. J. CHARLES BOLOMEY
SUPERLEC, Gif-sur-Yvette, France

9:30 - VII-4: The Depolarizing Term in Electromagnetic Vector Diffraction
Tomography
MR. NABIL SOLIMAN, MR. BRIAN D. JAMES
DR. ALEXANDER B. KOSTINSKI, PROF. WOLFGANG-M. BOERNER
UIC-EECS/CL, CHICAGO, IL./USA

10:00 to 10:30 COFFEE BREAK

SESSION VIII

10:30 to 12:30 - **POLARIMETRIC TOMOGRAPHIC METHODS FOR THE IMAGING OF CONCEALED OBJECTS**

Chairman: PROF. HANS BRAND
University of Erlangen-Nürnberg, Erlangen, FR Germany

10:30 - VIII-1: Comparison of Acoustic and Microwave Tomographic Measurements of Concealed Objects

MR. MARKUS VESTER
Siemens AG, Zentral-labor, Erlangen, FRG
PROF. HELMUT ERMERT
Ruhr-Universität, Bochum, FRG

11:00 - VIII-2: Microwave Diffraction Tomography in Underground Target Imagery

PROF. HANS BLOK
Technical University Delft, Delft, NL

11:30 - VIII-3: Polarimetric Random Signal Processing in Underground Radar Imaging

PROF. TSUTOMU SUZUKI
Denki Tsushin Daigaku, Chofu-Shi
Tokyo, Japan

12:00 - VIII-4: Application of the generalized pencil of functions method to polarimetric transient data scattered from buried objects

DR. TAPAN K. SARKAR
Syracuse University, Syracuse N.Y.

12:30 to 13:00 - **LUNCH BREAK** (Short Sandwich Pick-Up Type Luncheon)

SCI-CUL-TOUR I

13:00 to 21:30 - SCIENTIFIC/CULTURAL TOUR: HEIDENHEIM/Brenz-OBERKOCHEN-ULM-DINKELSBUEHL/ANSBACH

Co-Chairmen: DR. RUDOLF GROSSKOPF, Director
CARL ZEISS AG, Electronics R&D Center, Oberkochen, FRG
PROF. DR.-ING. GERHARD BOUCKE, Director
AEG Radio & Radar Systems Div., ULM, FRG

13:00 - **DEPARTURE FROM KUR-RESIDENZ HOTEL by Tour Bus**

14:30 to 16:30 - **VISITS OF CARL ZEISS OR AEG R&D LABORATORIES**

- (i) VISIT OF CARL ZEISS AG
Electronics Research & Development Center
Oberkochen/Kochel, FRG
- (ii) VISIT OF AEG Radio & Radar Systems Division
Ulm/Donau, FRG

16:30 - **DEPARTURE FROM ULM TO DINKELSBUEHL**

17:00 - DEPARTURE FROM OBERKOCHEN TO DINKELSBUEHL
 17:45 to 18:45 - Guided Tour of Dinkelsbühl, Visits of the "Bayerische Landesgartenschau 1988", and/or of the Gothic Cathedral
 19:00 to 20:30 - SUPPER at "Die SCHRANNE", Weinmarkt 7, Dinkelsühl, FRG
 20:45 - DEPARTURE FROM DINKELSBUEHL TO BAD WINDSHEIM BY TOUR BUS
 21:30 - Arrival at KuK-Hotel
 22:00 - DAY'S END: HOTEL AT REST (NOISE!)

THURSDAY, 22 SEPTEMBER 1988

6:00 MORNING CALL

6:45 to 7:45 - BREAKFAST

SESSION IX

8:00 to 10:00 - POLARIMETRIC VECTOR SIGNAL PROCESSING

Chairman: MR. LLOYD W. ROOT
 MICOM, Redstone Arsenal, AL./USA

8:00 - IX-1: Advances in Polarimetric Radar Device Technology/Signal Processing for Radar Remote Sensing
 DR. ANDRÉ J. POELMAN
 SHAPE-TC, The Hague, NL

8:30 - IX-2: The Design of Dual Polarimetric Integrated Microstrip Antenna Systems with Adaptive Polarization State Switching
 PROF. KIYOSHI ITOH
 Hokkaido Daigaku
 Sapporo, Hokkaido, Japan

9:00 - IX-3: Advances in Polarimetric Radiometry
 DR.-ING. GERD SCHALLER
 PROF. HANS BRAND
 University of Erlangen-Nürnberg, Erlangen, FRG

9:30 - IX-4: Multi-Spectral, Multi-static Polarimetric Signal Processing
 PROF. ALFONSO FARINA
 Selenia, Rome, Italy

9:30 to 10:30 - COFFEE BREAK

SESSION X

10:30 to 12:30 - POLARIMETRIC MULTI-STATIC & MULTI-SPECTRAL IMAGING

Chairman: MR. DONALD R. WEHNER
 Radar Div., NOSC, San Diego, CA./USA

10:30 - X-1: Basic Polarimetric Measurements in Monostatic and Bistatic Radar Imaging
 PROF. WERNER WIESBECK
 Technical Univ. Karlsruhe, Karlsruhe, FRG

- 11:00 - X-2: Polarimetric Scatterometry
 PROF. DAG T. GJESSING
 DR.-ING. JENS HJELMSTAD
 NTNF-PFM, Kjeller, Norway
- 11:30 - X-3: Computer-Aided Design of Multistatic/Multispectral Target RCS
 Scattering Matrices of Complicated Shapes
 PROF. SHUNG-WU LEE
 UIUC-ECE/EL, Urbana, IL/USA
 PROF. HAO LING
 UTA-ECE, Austin, TX/USA
- 11:50 - X-4: Polarimetric (Scattering Matrix) Bi-Static Target Imaging:
 Polarimetric Model for Multipath Imaging
 PROF. SUJEET K. CHAUDHURI
 University of Waterloo, Waterloo, ONT/Canada
 PROF. WOLFGANG-M. BOERNER
 UIC-EECS/CL, Chicago, IL./USA
- 12:10 - X-5: Plasma Resonance Effects in Radar Backscattering from Meteor Trails as
 Studied by the Scattering Matrix Method
 DR. SAMUEL P. WEI
 Boeing, Kent Space Center, Kent, WA/USA

12:30 to 13:45 - **LUNCH BREAK**

SESSION XI

- 13:45 to 15:15 - **POLARIMETRIC SAR/ISAR IMAGING**
 Chairman: MR. HANS DOLEZALEK
 Office of Naval Research, Arlington, VA./USA
- 13:45 - XI-1: Classification of Scattering Behavior
 Using POL-RAD/SAR Data
 DR. JAKOB VAN ZYL
 CAL-TEC/JPL, Pasadena, CA
- 14:15 - XI-2: Polarization Filtering of POL-SAR DATA
 DR. PASCALE DUBOIS
 CAL-TEC/JPL, Pasadena, CA/USA
- 14:35 - XI-3: The Polarimetric Matched Image Filter and
 its Application to POL-SAR Imaging
 MR. BRIAN D. JAMES
 DR. ALEXANDER B. KOSTINSKI
 PROF. WOLFGANG-M. BOERNER
 UIC-EECS/CL, Chicago, IL./USA
- 14:55 - XI-4: Theoretical Models for Polarimetric Microwave
 Remote Sensing of Earth Terrain
 DR. MAURICE BORGEAUD
 DR. ROBERT T. SHIN
 PROF. JIN-AU KONG
 MIT-EECS/EL, Boston, MA.

15:15 to 15:45 - **TEA BREAK**

MEETING WDG-3

15:45 to 17:45 - **WORKING DISCUSSION GROUP ACTIVITIES: PREPARATION OF FINAL REPORTS (W-1 to W-6)**

Chairmen: PROF. SUJEET K. CHAUDHURI
University of Waterloo, Waterloo, ONT/Canada

15:45 - Preparation of Final Reports of Individual Groups W-1 to W-6
PROF. DAG T. GJESSING
University of Tromsø, Tromsø, Norway

16:30 - Ten-Minute Summaries by Each Group's Reporters

W-1*: PROF. KIYOHICO ITOH and DR. SAMUEL P. WEI
W-2*: DR. DAVID E. STEIN and DR. REINHART HAMMEL
W-3*: DR. MARKUS VESTER and DR. MAURICE BERGEAUD
W-4*: DR. ALEXANDER B. KOSTINSKI and DR. BERND RÖDE
W-5*: DR. LEO LIGTHART and PROF. TSUTOMU SUZUKI
W-6*: DR. WALTER K. FLOOD and DR. ROBERT SERAFIN

* Final Group Reports will be published in the Workshop Proceedings

17:30 - Adjournment

17:45 to 21:30 - VISIT OF THE FRANKONIAN OPEN-AIR MUSEUM (Registration for Participation and Diet Requests to be forwarded by Tuesday, 1988 Sept. 20 noon to ARW-Sekretariat, Room A)

17:45 - DEPARTURE BY BUS FROM KUK HOTEL

18:00 to 20:00 - Viewing of OPEN-AIR MUSEUM with Guide

20:00 to 21:15 - "KARPFENESSEN im Museums-Restaurant":
Entertainment by Windsheimer Sänger

21:30 - DEPARTURE OF WORKSHOP BUSES

22:00 - DAY'S END: "HOTEL AT REST" (NOISE!)

FRIDAY, 23 SEPTEMBER 1988

6:00 MORNING CALL

6:45 to 7:45 - BREAKFAST

SESSION XII

8:00 to 10:00 - **STATISTICAL METHODS IN POLARIMETRIC REMOTE SENSING**

Chairman: DR. IRWIN D. OLIN
Naval Research Laboratory, Washington DC

8:00 - XII-1: Polarimetric Doppler Processing in Radar Remote
Sensing of Dynamically Moving Scatterer Ensembles

DR. DUSAN ZRNIC
DR. RICHARD J. DOVIAK
NOAA-TRL-NSSL, NORMAN, OK/USA

- 8:30 - XII-2: Statistics of Stokes Parameters in Radar Polarimetry
PROF. RICHARD BARAKAT
Applied Sciences Div., Harvard University
Cambridge, MA./USA
- 9:00 - XII-3: Selection of Suitable Probability Density Distribution
Functions in Radar Polarimetry: The Weibull Distribution
PROF. MATSUO SEKINE
Tokyo Kogyo Daigaku, Nagatsuta
Yokohama-Shi, Japan
- 9:20 - XII-4: On Adaptive Radar Polarimetry: Concepts of Implementation
PROF. LEONID B. FREISER
Northrop University, Los Angeles, CA./USA
- 9:40 - XII-5: Angle Tracking of Partially Polarized Signals: Diversity
Methods based on Level Crossing Theory
DR. DANIEL D. CARPENTER
TRW Space & Defense Div.
ER Segundo, CA/USA

10:00 to 10:30 - COFFEE BREAK

SESSION XIII

- 10:30 to 12:30 - POLARIMETRIC RADAR METEOROLOGY
Chairman: DR. WALTER FLOOD
Army Research Office
Research Triangle Park, N.C./USA
- 10:30 - XIII-1: A Critical Assessment of the Historical Development of
Polarimetric Radar Meteorology;
Where do we come from, where do we go?
PROF. THOMAS A. SELIGA
Pennsylvania State Univ., College Park, PA./USA
- 11:00 - XIII-2: Dual Polarization Meteorological Radar Developments
at Higher Power Levels
DR. EUGENE A. MUELLER
MR. GERALD D. NESPOR
UIUC/ISWS-CHILL Radar
Champaign, Urbana, IL./USA
- 11:20 - XIII-3: Polarimetric Radar Application to Meteorology and
Scattering Matrix Measurements
PROF. YAHIA M.M. ANIAR
Royal Military College
Kingston, ONT, Canada
- 11:40 - XIII-4: The Delft Polarimetric Meteorologic Radar System
DR. LEO P. LIGTHART
Center for Remote Sensing
Delft University of Technology

12:10 - XIII-5: Polarization Antenna Patterns from NCAR's CP-2
Meteorological Radar
DR. JEFFEREY KEELER
NCAR, Boulder, CO./USA

12:30 to 13:45 - LUNCH BREAK

SESSION XIV

13:45 to 15:15 - POLARIMETRIC SIGNATURES IN RADAR METEOROLOGY,
OCEANOGRAPHY, AGRICULTURE & FORESTRY

Chairman: PROF. DR.-ING. ALFONS KESSLER
Technische Hochschule Darmstadt, FRG

13:45 - XIV-1: Polarimetric Radar Measurements in Convective Storms
PROF. VISWA-NATHAN N. BRINGI
Colorado State Univ., Collins, CO./USA

14:15 - XIV-2: Towards an Understanding of the Effects of Propagation
through Rain on Data from Polarization Diversity Radars
PROF. ANTHONY R. HOLT
University of Essex, Colchester, England, UK

14:35 - XIV-3: Snowfall and Rainfall Observations Using the DND Dual
Polarization Radar
DR. FUMIO YOSHINO
Doboku Kenkyo Jo, Tsukuba, Japan

14:55 - XIV-4: Sensitivity of Two Polarimetric Backscatter Models for
Sea-ice
DR. DALE P. WINEBRENNER
Applied Physics Lab., University of Washington
PROF. LEUNG TSANG
PROF. AKIRO ISHIMARU
Dept. of Electrical Engr.
University of Washington
Seattle, WA./USA

15:15 - XIV-5: Polarimetric Signatures of Vegetated and Forrested Terrain
DR. HARUTO HIROSAWA
Institute of Space & Astronautical Sciences
ISAS, Sagamihara-Shi, Kanagawa-ken, Japan

15:45 to 16:15 - TEA BREAK

MEETING WDG-4

16:15 to 17:15 - FINAL WORKING DISCUSSION GROUP MEETING (Lecture center)

Chairman: DR. ROBERT J. SERAFIN
NCAR, Boulder, CO./USA

Submission of Final Reports by Group Reporters

Preparation of Final Overall Statement

SESSION XV

17:15 to 18:15 - **FINAL SESSION**

Chairman: DR. FREDERIC MOLINET
Soc. Moth, Plessis-Robinson, France

17:15 - Concluding Remarks

PROF. PIERRE C. SABATIER
USTL, Montpellier, France

17:30 - Instructions on Submission of Final Report Forms

DR. ERNST LÜNEBURG

17:45 - Summary of Working Discussion Group Reports

DR. MARTIN VOGEL

18:00 - Procedures for the Publication of the Workshop Proceedings

PROF. WOLFGANG-M. BOERNER

18:15 - Adjournment

18:00 to 19:00 - **SETTLING OF HOTEL BILLS**

(Please, make use of any spare time during Friday noon/afternoon for settling your hotel bills and for preparation of Saturday's Scientific Tour Departure)

WORKSHOP BANQUET (XVI)

19:00 to 21:00

Hosts: HERR ROLF K. ERLNBACH, KUK HOTEL, MANAGER
FRAU JUTTA BROCHHOFF, KuK Hotel, Vice-Manageress

19:00 to 20:00 - **DINNER**

20:00 - Introduction of Guests of Honor

DR. WOLFGANG KEYDEL, DFVLR, Oberpfaffenhofen, FRG

20:15 - Thanks to the Hosts and the Sponsors

MR. LEONARD A. CRAM, THORN-EMI, Somerset, UK

20:30 - XVI-1: **The Dual Polarization Doppler C-Band Radar Meteorological Instrumentation Facility at DFVLR-Oberpfaffenhofen**

DR.-ING. ARNO SCHROTH

DR.-ING. KARL TRAGL

DFVLR, REMOTE SENSING DIV./OPH.

21:20 - XVI-2: **Detailed Instructions on the Scientific/Cultural Tour of Saturday via Rothenburg and Ulm to Oberpfaffenhofen**

DR.-ING. HELMUT SÜSS, DFVLR, Oberpfaffenhofen, FRG

DR.-ING. SIEGFRIED OSTERRIEDER, GHS, Ravensburg, FRG

PROF. WERNER WIEBECK, TÜK, Karlsruhe, FRG

21:40 - Adjournment

22:00 - **DAY'S END" HOTEL AT REST" (NOISE!)**

SATURDAY, 24 SEPTEMBER 1988

6:00 MORNING CALL

6:45 to 7:45 - BREAKFAST

7:45 to 8:15 - Settling of Bills and Clearing of Hotel Rooms

SCI-CUL-TOUR II

8:15 to 8:30 - CULTURAL/SCIENTIFIC TOUR: ROTHENBURG-ULM-AUGSBURG-

OBERPFAFFENHOFEN-MUNICH

Tour Co-Chairmen: DR. WOLFGANG KEYDEL
PROF. WERNER WIEBECK
PROF. WOLFGANG-M. BOERNER

8:30 - DEPARTURE (Note, Luggage of tour participants will be taken along with the tour buses, as advised during registration)

9:00 - ARRIVAL in ROTHENBURG (Visits will include guided sightseeing tour, brief shopping, viewing of St. Jakob Cathedral and City Hall)

10:30 - Departure from Rothenburg (Ride along new Autobahn to Ulm)

11:45 - Arrival at Ulm (Viewing of City Center and ULMER DOM)

12:30 - Departure from Ulm and distribution of lunch bags

14:00 - Arrival at DFVLR-Oberpfaffenhofen

14:00 to 17:30 - VIEWING OF DFVLR C-BAND DUAL POLARIZATION DOPPLER RADAR FACILITY

14:15 - Welcome of visitors and introduction to the mission of DFVLR at Oberpfaffenhofen

PROF. DR. HEINZ HÄBERLE, Director, DFVLR-OPH

14:30 - The DFVLR-NE-HF Microwave Remote Sensing Center

DR. WOLFGANG KEYDEL, Director, DFVLR-NE-HF

14:45 - The DFVLR Institute of the Physics for the Atmosphere, Polarimetric Radar Meteorology Research Program

DR. MANFRED REINHART, Director, DFVLR-IPA

15:00 - Guided tour through the DFVLR Dual Polarization Radar Meteorological Instrumentation Facility

DR. ARNO SCHROTH, Chief, DFVLR-POL-RAD Research

16:15 - COFFEE BREAK: Final Come together at DFVLR Cafeteria

Host: DR. WOLFGANG KEYDEL

17:00 - Farewell Speech

PROF. WOLFGANG-M. BOERNER

17:30 - Departure of bus to Munich Central Station

18:30 - Farewell at München Hauptbahnhof